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**Electrodynamics of the Middle Atmosphere:
Superpressure Balloon Program**

**FINAL REPORT
NASA Grant NAGW-724**

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FINAL REPORT NAGW-724

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This grant partially supported the data analysis from a series of superpressure balloon payloads flown in 1983 and 1984. This "final report" is actually a report of research in progress because the grant has been continued but under a different grant number NAG5-635. The grant number and technical monitor were switched (from NASA Headquarters to NASA Goddard) for the convenience of NASA and NOT due to any request by the investigator. Nevertheless, the following report is provided to fulfill any legal requirements.

I. INTRODUCTION

In this experiment a comprehensive set of electrical parameters were measured during eight long-duration flights in the southern hemisphere stratosphere. These flights resulted in the largest vector electric field data set ever collected from the stratosphere which has been a treasure-trove of new phenomena. Since the stratosphere has never been electrodynamically sampled in this systematic manner before, it is perhaps not surprising that several new discoveries have been made and reported. These include the discovery of short term variability in the planetary scale electric current system, the unexpected observation of stratospheric conductivity variations over thunderstorms and the observation of direct stratospheric conductivity variations following a relatively small solar flare (Brightness 1 Normal). Furthermore, we have conducted major statistical studies of the large scale current systems, the stratospheric conductivity and the neutral gravity waves (from pressure and temperature data) using the entire data set.

Much of this data analysis so far has focused on the lower atmospheric current generators (thunderstorm and global circuit problems) only because an initial look at the data indicated that obvious new (or unstudied) phenomena were seen. Also, the time period of these flights was near solar minimum and included very little in the way of major magnetospheric or solar activity (only two ring current - i.e. Dst - events and one small solar flare). We have now begun a systematic analysis of the vector electric field and in particular the horizontal component which derives from ionospheric phenomena or from local atmospheric phenomena. The primary

thrust of the ongoing research is to obtain a better understanding of mid-latitude electrodynamical phenomena which perturb the horizontal electric field and current systems. In addition to the direct electric field measurements, we also have on-board measurements of magnetospheric Hiss (at 4.5 kHz), VLF electric field filters and vector magnetic field (for overhead current systems). As reported by Holzworth et al, (1983) the fair weather horizontal electric field appears to be of larger magnitude and to have a diurnal variation inconsistent with its source being the ionospheric dynamo.

II. SCIENTIFIC PROGRESS

The last balloon flight terminated in April 1984, and the earlier grants supported the initial data reduction of the satellite data (received by the French ARGOS platform on the Tiros satellites) into a format which could easily be used for scientific analysis. This data reduction was done jointly by NCAR, and the University of Washington. To summarize the past analysis record: we have had five papers accepted with a sixth just submitted and have presented eleven (including three invited) papers. The project actually started by NASA sending their half of the support to NSF so the University of Washington has only to deal with one grants officer. Therefore, the early papers acknowledge only the NSF grant number ATM82-12283. The NASA grant NAGW-724 is specifically acknowledged in the latest three papers which are included in the appendix.

The original proposal stated that we would look particularly at several specific questions including the cause of variations of the large scale (or global) current systems, investigation of the atmospheric-ionospheric-magnetospheric electrical coupling, and studies of various major events such as solar flares and magnetic storms. The subjects of the papers directly reflect on these research areas. In particular, it is interesting to note that analysis has proven the usefulness of the long duration balloon technique for solar-terrestrial coupling studies. Unlike all previous such experiments on zero-pressure balloons, we were up and flying prior to, during and following a solar flare (16 Feb 1984 with ground level cosmic ray and polar cap absorption events) as well as two world wide magnetic storms. The only previous vector stratospheric electric field data during a solar flare were obtained during the giant August 4, 1972 solar flare which has often been discounted as a qualified representative of *normal* solar-terrestrial coupling. Therefore, it is probably fair to say that, in spite of the low solar

activity, the data set is everything (and more) than we could have hoped for. Similarly, the publications and presentations are stirring up a lot of controversy because the new views of global current systems offered by these data are unconventional.

A. Important Results

This section will present a sample of the EMA data analysis results.

1. Global Circuit Variability

One of the first results to be presented from the data set was the discovery of short term variability of the global circuit. Prior to these flights, all the constant altitude simultaneous data were from flights lasting less than 24 hours (c.f. Markson, 1976). The short term variability is seen in our data by comparing the vertical electric field and conductivity data from multiple simultaneous balloon payloads as reported by Holzworth et al, 1984. By employing two balloons simultaneously one can eliminate to a large extent the small spatial scale variations. This spatial averaging allows high time resolution of the large scale fields. These vertical electric field data from two or more simultaneous payloads have been combined to study the planetary scale variability of the global circuit. Figure 1 shows a preliminary "geo-electric" index based on EMA balloon data for which the average daily variability (similar to the Carnegie Curve) has been removed in order to study the short term variability.

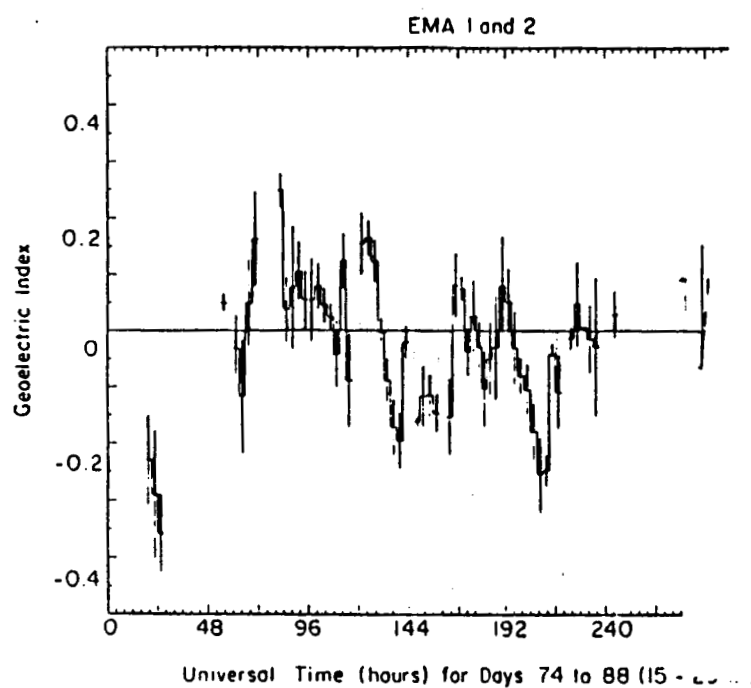


Figure 1: A preliminary Geo-Electric Index based on three hour averages of vertical current density from widely separated balloons. The Daily average variation has been removed. (From Norville and Holzworth, 1987)

2. Global Stratospheric Conductivity Measurements

In order to determine the large scale current density variability (as in figure 1) it has been necessary to analyze all the stratospheric conductivity data to determine the natural variability with geography. Figure 2 shows the four day segments from two different flights showing the basic nature of the conductivity to be slowly varying as the balloons move in latitude and longitude. Also, the absolute values of the positive and negative conductivity can be quite different depending on atmospheric aerosol levels (such as due to the extensive volcanism in 1983). It is the case for all the data from all the EMA balloons that the positive polar conductivity is slightly larger than the negative conductivity and in some cases can be more than a factor of two larger (see left panel below).

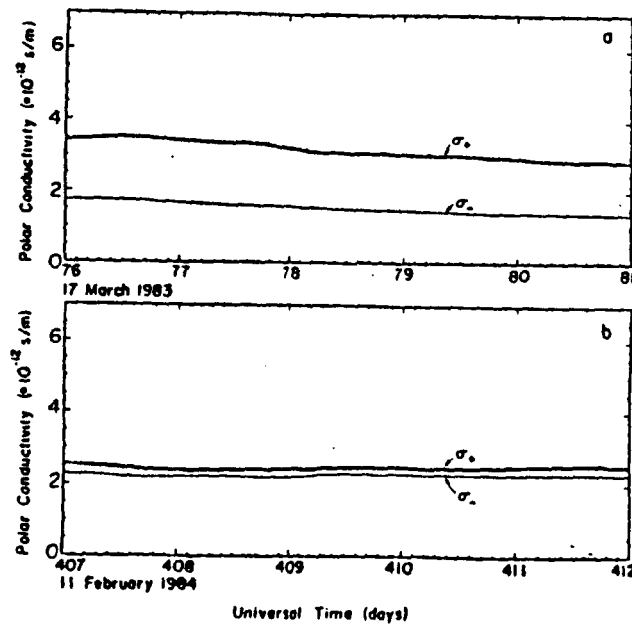


Figure 2. Positive and Negative Polar conductivity from two EMA flights. (From Norville and Holzworth, 1986)

The conductivity data from several flights have been plotted against balloon latitude in order to verify the expected latitudinal (λ) increase toward the poles. Figure 3 shows data from the two separate EMA flight programs (1983 and 1984) fit to a curve of the form $A + B \sin^4(\lambda)$. While this pattern had been known before, it is interesting to note that the vertical electric field did not show this pattern (or its inverse) but rather is not a strong function of latitude. Therefore the current density is seen to increase toward the poles.

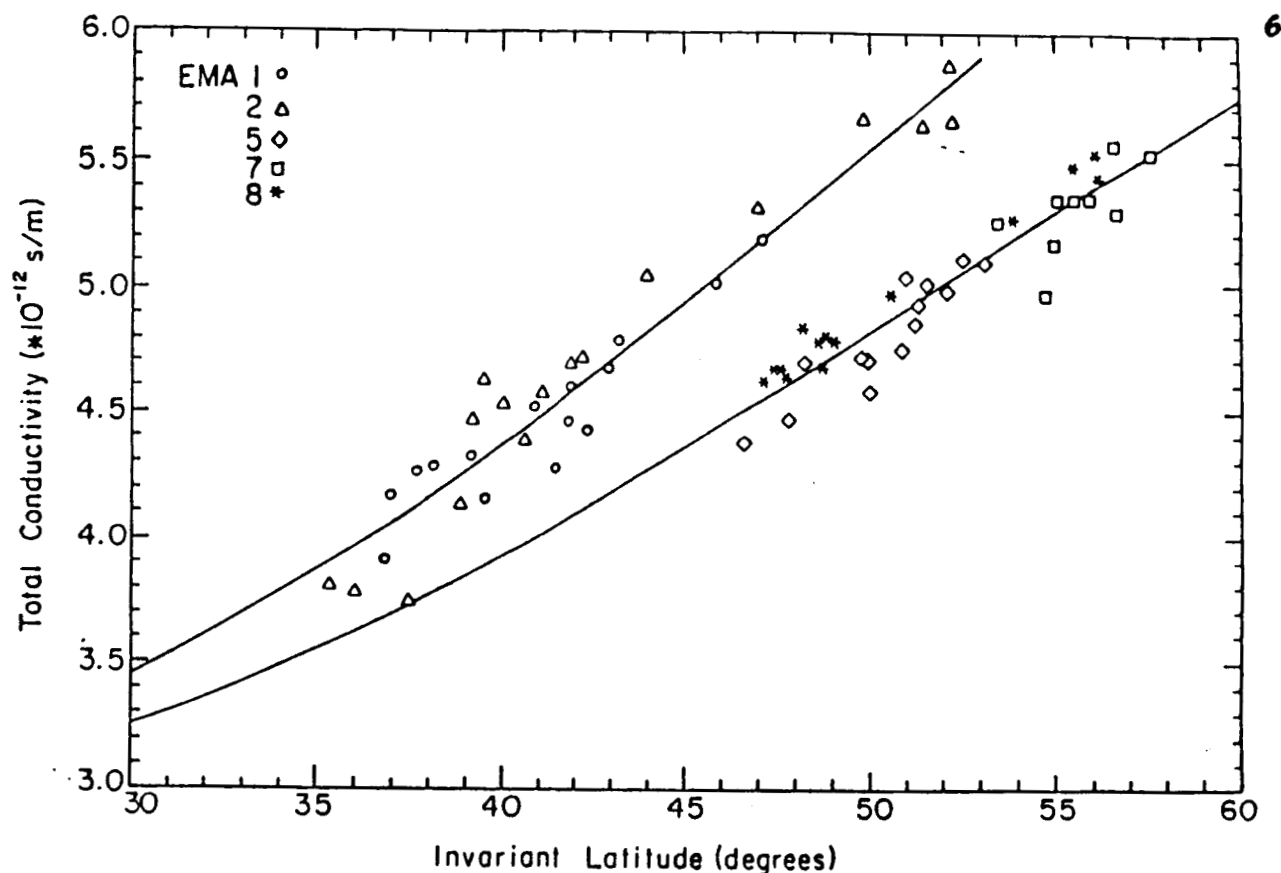


Figure 3. Conductivity versus Invariant Latitude for the two EMA flight sequences.

3. Conductivity variations following a solar flare and over thunderstorms

A good understanding of the atmospheric conductivity is one of the keys to understanding global electrodynamics. We have found that the conductivity in the stratosphere is variable both during extra-terrestrial events such as small flares and can also be perturbed by thunderstorms even up to 26 km altitudes. Neither of these two types of perturbations has been directly measured previously nor are the perturbations included in any theoretical studies on the global circuit (c.f. Hays and Roble, 1979, Ogawa, 1985, Makino and Ogawa, 1985).

Figure 4 presents the conductivity, vertical electric field and vertical current density for a few hours on February 16, 1984 following a solar flare. The flare resulted in a ground level cosmic ray event seen around the world at this time. This is the first time such short term direct conductivity variations in the stratosphere have been measured during a solar flare.

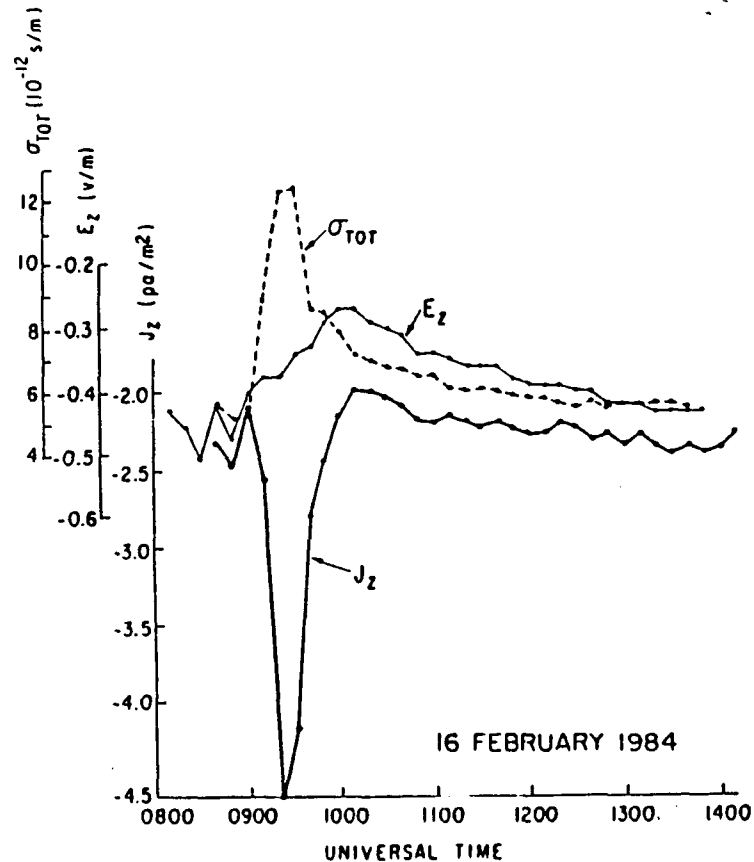


Figure 4: Total Conductivity, Vertical Electric Field and Vertical Current Density variations in the stratosphere following a solar flare of optical importance "1N".

All theoretical models of the global circuit current flow use a fair weather conductivity profile to connect thunderstorms with the ionosphere. The paper by Holzworth et al, 1986 describes factor of two changes in conductivity over thunderstorms and includes the results of a statistical study in which we found stratospheric conductivity increases in 87% of the most intense thunderstorms overflowed by EMA balloons.

4. Neutral Density Waves and Turbulence

Each of the EMA payloads was equipped with pressure and air temperature sensors with sampling rates of 40 seconds. These 40 second pressure and temperature data were only stored for 1 hour on-board the balloon payloads so the data set is not continuous, but comprised of typically 12 to 18 one hour blocks each day from each balloon. These data are being used in an extensive study of the atmospheric gravity waves and turbulence in the stratosphere. Fluctuations between about 2 minutes and (in some cases) up to 12 hours can be uniquely determined from these data.

Suprpressure balloons nominally float on a constant density surface (Lally, 1975) and therefore act as a Lagrangian point measurement of the neutral density wave/turbulence activity. Two types of oscillations are seen in our data: constant density variations in altitude and neutral buoyancy oscillations of the balloon itself. If the constant density surface (along with the balloon) moves up and down, the pressure and temperature should vary in phase (assuming an ideal gas equation of state). However, if the balloon moves along a vertical axis due to natural balloon buoyancy oscillations, the temperature and pressure will be out of phase. This is because at 26 km altitude the temperature is an increasing function with altitude, but the pressure is exponentially decreasing with altitude. These neutral Buoyancy Oscillations (NBO) have a period which is somewhat dependent on amplitude (i.e. not just simple harmonic motion) of about 2 to 4 minutes (Lally, 1975, Massman, 1978). While these NBO's interfere with any natural gravity waves or atmospheric turbulence at these periodicities, the observation of them confirms that the sensors are functioning properly. Therefore, to begin with we have concentrated on the long period gravity waves starting above the NBO period (i.e. periods greater than 4 minutes). Figure 5 gives an example of the raw temperature and pressure data in which can be seen both short period NBO variations (especially in the pressure sensor on this scale) and neutral density variations with periods of 8 to 12 minutes in which the temperature and pressure vary in phase. Figure 6 shows the average power spectra from two EMA balloons for several days each. The raw spectra are averaged in frequency space from several one hour data blocks. Between 40 seconds and the NBO the spectrum follows a power law of about $f^{-2.6}$. This is much steeper than the $-5/3$ power law expected for some types of turbulence. It will be interesting to compare these observations to the MST radar and other studies of atmospheric gravity waves and turbulence because these Lagrangian point measurements are unique in their extensive time series and temporal resolution.

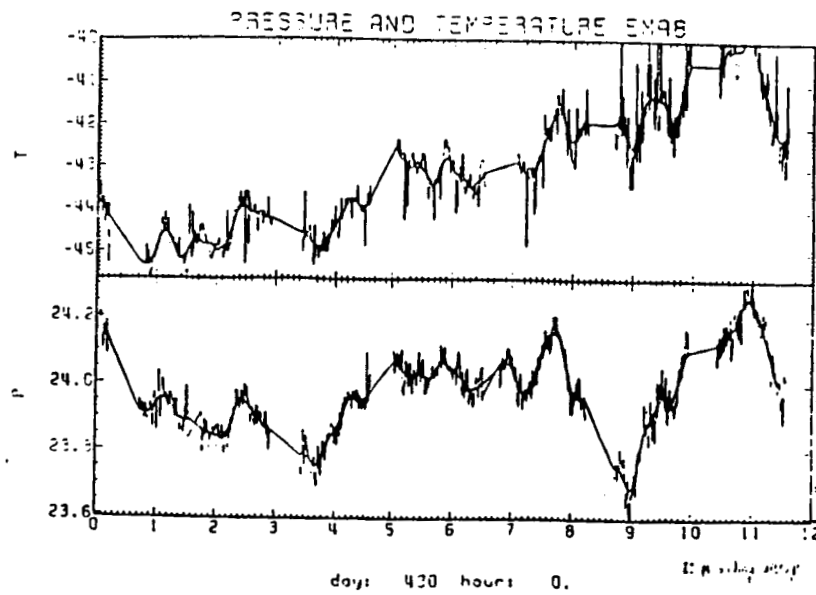


Figure 5. Raw temperature and pressure data showing NBO and neutral density fluctuations.

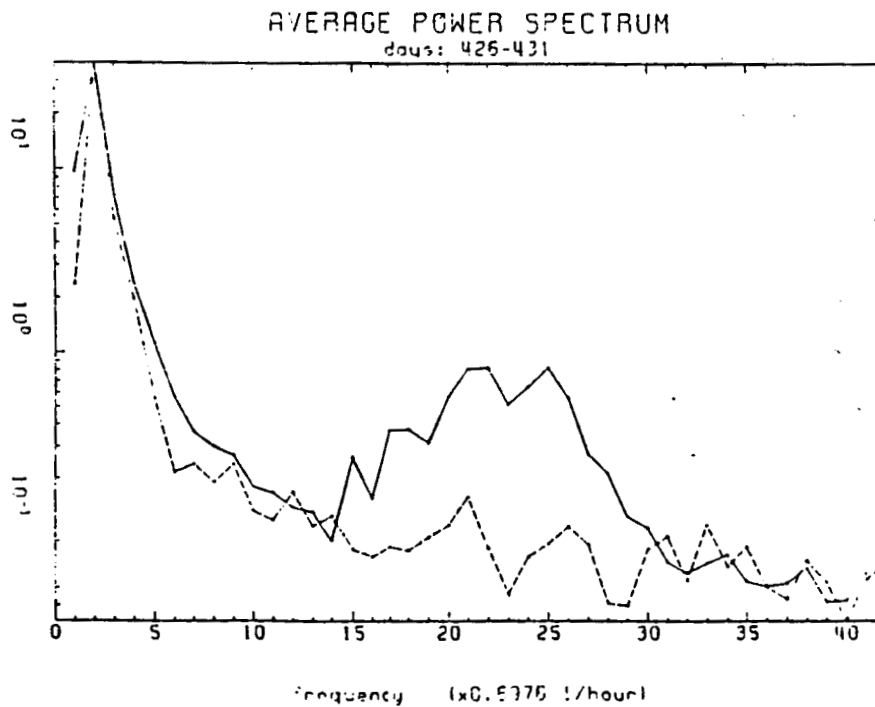


Figure 6. Sample of the average power spectra of the temperature and pressure for three days from one EMA payload. The NBO's are clearly seen in the pressure data near a period of 4 minutes. The temperature sensors tend to have more noise at this period and do not show the NBO very clearly most of the time.

B. Publications, Presentations and Drafts

Publications (also see the Appendix)

1. Holzworth, R. H., Electrodynamics of the stratosphere using 5000 m^3 Superpressure balloons, in *Scientific Ballooning III*, W. Reidler and M. Fredrich (eds.), Pergamon Press, Oxford, 1983.
2. Powell, S. P., "An on-board microprocessor system for processing electric field signals on superpressure balloons", Masters Thesis, Dept. of Electrical Engineering, Cornell Univ., Ithaca, N.Y. 1983.
3. Holzworth, R. H., T. Onsager, P. Kintner and S. Powell, Planetary Scale Variability of the fair weather vertical electric field, *Phys. Rev. Lett.*, 53, 1398, 1984.
4. Holzworth, R. H., K. Norville, P. M. Kintner and S. Powell, Stratospheric Conductivity Variations over Thunderstorms, *J. Geophys. Res.*, 91, 13257-13263, 1986.
5. Holzworth, R. H. and H. Volland, "Do we need a Geoelectric Index?", *EOS Trans. Am. Geophys. Union*, 67, 545-548, 1986.
6. Norville, K. W. and R. H. Holzworth, Global circuit variability from multiple stratospheric electric field measurements, *J. Geophys. Res.*, 91, accepted and in press, 1987.

Presentations

1. Holzworth, R., M. Kelley, P. Kintner, R. Williamson, A. Shaw, R. Dowden, B. Edgar, T. Onsager and S. Powell, "Electric field measurements from superpressure balloon-borne payloads", Spring AGU meeting, (see *EOS*, 64, 295, 1983).
2. Holzworth, R., P. Kintner, T. Onsager and S. Powell, "Global electric field variations in the stratosphere", Fall AGU meeting (see *EOS*, 64, 664, 1983).
3. Holzworth, R., K. Norville, P. Kintner and S. Powell, "Variability of the source of atmospheric electricity", Paper 10.6 given at the VII International Conf. on Atmospheric Electricity, Am. Meteor. Soc., Albany, NY, June 8, 1984.
4. Norville, K., R. Holzworth and P. Kintner, "Vertical electric fields and currents in the southern hemispheric stratosphere", Fall AGU meeting (see *EOS*, 65, 1033, 1984).
5. Holzworth, R. H. Southern Hemisphere Balloon Data, (Invited Paper), GISMOS Workshop, NCAR/NSF, Boulder Oct 24 - 26, 1984.
6. Dowden, R. and R. Holzworth, Whistler Duct Cross-sections Implied by Multi-balloon Measurements of VLF Hiss, IRSI Meeting, Vancouver, B.C., Canada, June 17-22, 1985
7. Holzworth, R., Thunderstorm Electrical Phenomena in the Upper Atmosphere, (Invited Seminar), UMIST, Manchester England, 21 June, 1985
8. Holzworth, R. H., Electric Field Measurements at Middle Atmospheric Heights, (Invited Review), IAGA/IUGG meeting, Prague, Czechoslovakia, Aug 5-17, 1985.

9. Dowden, R and R. Holzworth, VLF Background noise at 26 km alt, IAGA/Prague Aug 5-17, 1985
10. Holzworth, R. H., "Global electric circuit variability determined from *in-situ* measurements" (invited paper) at the Spring AGU meeting, Baltimore, MD, May 1986.
11. Holzworth, R. H., "Electric fields in the middle atmosphere" Invited Review just presented at the VIth International Symposium on STP at the XXVI General Assembly of the Committee on Space Research (COSPAR) of the International Council of Scientific Unions, in Toulouse, France, July 4, 1986.

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APPENDIX

Published papers acknowledging NAGW-724

Do We Need a Geoelectric Index?

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Introduction

We might put the question slightly differently: What scientific problems require knowledge of the global variability of lower atmospheric electric generators? In this paper, we present our view of the necessity of quantifying global electrical variability and discuss some potential uses of and available methods for producing a geoelectric index.

During this last decade, we have observed an increasing interest in the field of atmospheric electricity. At the 1985 AGU Fall Meeting in San Francisco, Calif., there were seven half-day sessions on various aspects of atmospheric electricity—a great increase over past years (see the abstract listings for the Atmospheric Sciences and SPR: Magnetospheric Physics sessions in *Eos*, November 12, 1985, pp. 815-842 and 1028-1055). This area of interest covers thunderstorm electrification, lightning, and sferics, as well as lightning-induced magnetospheric effects and solar-terrestrial electromagnetic coupling. For many aspects of these studies, it would be advantageous to have a number that is a measure of present global electrical activity, such as thunderstorm occurrence, number of lightning events, or ionospheric electric potential relative to the earth [see also *Markson and Muir*, 1980]. Furthermore, there are many other areas of research that would benefit from a geoelectric index, such as meteorology and atmospheric science.

A geoelectric index should be similar in utility to other solar-terrestrial activity indicators, such as the well-known solar sunspot number or the various geomagnetic indices [see *Rostoker*, 1972]. These numbers are relatively simple to derive from ground-based observations on a routine basis. They are reliable, reproducible from alternative data sets, and historically available for many decades. Although the solar sunspot number is not an optimum index of solar activity (the 10.7-cm solar radio emission or the satellite-based UV observations are better), its simplicity and the length of the available data base outweigh its disadvantages. The same is true for the geomagnetic indices. Geomagnetic observatories exist all over the world. They continuously report data of the variable geomagnetic field, which (when appropriately sampled) gives a fair indication of the ceaselessly varying ionospheric and magnetospheric electric current systems.

The usefulness of these indices is beyond doubt, and the question may therefore be raised whether a geoelectric index might be

of comparable value in the near or distant future. Along this line, it is interesting to note that recent research has shown that the large scale return currents of the global circuit are variable by factors of two from the mean daily variation. *Holzworth et al.* [1984] report that simultaneous balloon-borne electric field measurements from widely separated balloons (over 1000 km) in the stratosphere often have the same magnitude and the same temporal variation but nonetheless differ drastically from the "expected" Carnegie Curve (which represents the average universal time variation of the surface electric field: about $\pm 20\%$ – 15% variability from the mean; compare *Whipple* [1929]). Thus we now suspect that the global circuit is variable on a time scale of tens of minutes.

Who Are the Potential Users of a Geoelectric Index?

Before we evaluate the different possible methods for deriving a geoelectric index, we will first deal with the question of who might be interested in using such an index and why. We will limit ourselves to three general areas that would greatly benefit from a geoelectric index: atmospheric and space electrodynamics, atmospheric science, and meteorological forecasting. For each of these research areas, we will illustrate basic science problems that might not be solved without a quantitative measure of global electrical activity or the source distribution function. Within atmospheric and space electrodynamics, we will discuss outstanding scientific questions concerning the global circuit, solar-terrestrial coupling, lightning effects on the ionosphere and magnetosphere, and the possible identification of mesospheric electric field generators. Atmospheric science examples will include thunderstorm-generated or -transported molecules, which play an important role in stratospheric chemistry and planetary wave forcing by thunderstorms. Under meteorology, we will discuss the need for better fog forecasting.

Problems in Atmospheric and Space Electrodynamics

The Global Circuit

Wilson's [1920] hypothesis is that thunderstorms are the main generators of the global electric circuit, causing an electric potential between earth and the ionosphere of about 200–500 kV and electric current density within the fair weather areas of a few picoamperes per square meter. Although it is widely accepted, this hypothesis has not yet been proven beyond doubt [see *Dolezalik*, 1972]. We know that a typical thunderstorm generates an upward dc electric current of the order of 1 A and that extrapolation from meteorological data suggests that ~1000–2000 thunderstorms are active at any time. On the other hand, lightning currents are assumed to close (at least partly) the global circuit between the ground and the storm clouds (Figure 1). The existing data do not

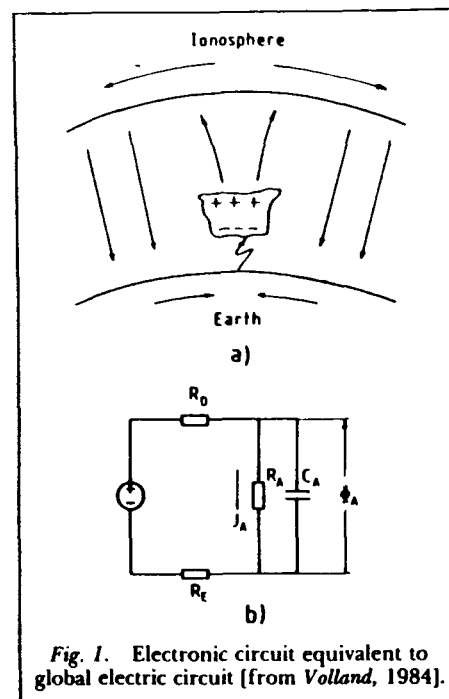


Fig. 1. Electronic circuit equivalent to global electric circuit [from *Volland*, 1984].

allow the determination of a quantitative relationship between the various parts of the global electric circuit. A geoelectric index, along with an extensive short-term measurement program of electrical parameters by airborne, balloon-borne, and satellite-borne detectors, will be necessary to quantitatively understand the global circuit.

Solar-Terrestrial Coupling Processes

It is now widely recognized that the current systems driven by global thunderstorms and by magnetospheric plasma phenomena coexist in the middle atmosphere and above. For instance, recent models of thunderstorm current systems [e.g., *Tzur and Roble*, 1985] show that most of the return current from a thunderstorm generator that penetrates the tropopause flows globally through the ionosphere and along plasmaspheric magnetic field lines. Furthermore, the first experimental evidence of these thunderstorm dc current systems up to at least 70 km altitude (well above the classic "electrosphere": see *Chalmers*, [1967]) has just been reported [*Holzworth et al.*, 1985]. The opposite situation occurs for large-scale electric fields in the magnetosphere, which have long been known to drive current systems down at least to the stratosphere [*Mozar and Serlin*, 1969]. Furthermore, the typical temporal variability of a magnetospheric substorm is of the same order as a large thunderstorm (about 1 hour, say). For these reasons, we suggest that a quantitative estimate of the dynamical variability of the tropospheric source of electric phenomena (such as thunderstorms) is necessary before the importance of upward or downward coupling of electrical phenomena can be clearly addressed. For instance, identifying an effect of a 10% variation in the ionospheric potential caused by solar or magnetospheric phenomena [*Herman and Goldberg*, 1978] would be nearly impossible without knowledge of the natural variations of the ionospheric potential caused by global thunderstorms (or other tropospheric generators).

ORIGINAL PAGE IS OF POOR QUALITY

Lightning Effects on the Ionosphere/Magnetosphere

We have known for decades [Helliwell, 1965] that lightning generates broad electromagnetic frequency spectra and that some of that wave energy propagates into the magnetosphere, where it interacts with ambient plasma particles. The lightning-generated whistler wave propagates along density gradients in the magnetosphere and can be amplified by resonant wave-particle plasma interactions. The process of amplifying this wave also results in pitch angle scattering of trapped radiation, which is then precipitated into the upper atmosphere [Schulz and Lanzerotti, 1974]. In this case the lightning-generated whistler wave acts only as a test wave that results in the release of stored magnetospheric particle energy. However, it has been discovered recently that the electric waveform from a lightning event can have a significant amplitude in the ionosphere up to at least 150 km altitude [Kelley et al., 1985]. Kelley et al. reported electric field amplitudes over an order of magnitude larger than ambient mid-latitude ionospheric fields with pulse time durations longer than the local plasma relaxation time. Furthermore, the Kelley et al. measurements suggest that the electric transient contains a significant electric field component parallel to the magnetic field. This could result in a significant energy input to the ionosphere through ohmic heating, or it might result in anomalous increase of resistivity through collective plasma processes. Thus, for the first time, we have evidence that thunderstorms can be an important source of free energy for ionospheric plasma processes. These ionospheric plasma phenomena that are directly attributable to thunderstorms and lightning may be important in the global ionospheric energy budget, especially at mid- and low latitudes, but we need an active rocket and satellite program, coupled with a geoelectric index, to help answer the many questions these new experimental measurements raise.

Mesospheric Generators

In the mid 1970s, following a series of rocket flights, Tyutin [1976] reported anomalously large values of the measured vertical electric field near 60 km altitude. Since that time, other investigators [Hale et al., 1981; Maynard et al., 1981] have also reported large electric fields up to several volts per meter in the mesosphere. The possibility that these investigators have discovered a new source of electric fields in the earth's environment is an exciting one. It could effect our understanding of the entire area of solar-terrestrial electrical coupling. However, these observations have been questioned by other rocket experimenters [Bering et al., 1980; Kelley et al., 1983], who have pointed out the difficulty of making electric field measurements in this altitude region. The interpretation of the Tyutin et al. and subsequent measurements of volt per meter electric fields between 50 and 80 km is difficult in view of several direct comparisons between ionospheric electric fields and those measured by balloons in the stratosphere [Kelley and Mozer, 1975]. Furthermore, the large body of ionospheric electric field data inferred from upward mapping of stratospheric balloon-borne electric field measurements has accurately accounted for many ionospheric and magnetospheric phe-

nomena, such as ionospheric convection patterns [Mozer and Lucht, 1974] and radial diffusion of radiation belt particles [Holzworth and Mozer, 1979a].

We must clear up the question of whether mesospheric generators exist and, if so, to what extent they affect the large-scale electrical coupling question. Again, as in the other cases, this will be difficult without some temporal index showing the variability of the other known sources, including the global electric circuit (using a geoelectric index) as well as more traditional magnetic activity indicators to give an idea of the ionospheric/magnetospheric temporal variability. These indices will be needed, along with rocket, satellite, radar, and balloon programs, to diagnose the problem of mesospheric generators.

Atmospheric Chemistry Stratospheric Ozone Cycle

In addition to their importance to the lower atmospheric electrical circuit, thunderstorms are known to be a source of nitrous oxide [Levine et al., 1981]. The importance of nitrous oxide to the stratospheric ozone cycle is well known: N_2O is a source of NO, which catalytically destroys ozone. However, the global budget of N_2O is still under debate [see Brasseur and Solomon, 1984]. N_2O is generated by biological and industrial processes, as well as by lightning and corona currents below thunderstorms. While it can be argued that sources that are not lightning related produce the greater amount [Hill et al., 1984], thunderstorm updrafts may be the most effective transport mechanism for getting the N_2O into the stratosphere. Thunderstorms and tall cumulus clouds may be two of the most important sources for water vapor in the stratosphere, since the largest ones penetrate well above the tropopause [Vonnegut, 1982]. Of course, just getting a parcel of air containing tropospheric constituents into the stratosphere is not sufficient to keep it there: that requires mixing stratospheric air with the injected air. Again, however, thunderstorms may play an important role, as may be inferred by the increased turbulence in the stratosphere over thunderstorms [Lee, 1977].

While the need for a better understanding of stratospheric ozone dynamics and secular variability is clear, its potential importance to the global variability caused by thunderstorm-generated and -transported nitrous oxides is not well understood. The availability of a geoelectric index related to global thunderstorm activity will be required to assess this possibly very important source of N_2O . This is also an important source of many other important molecules in the stratosphere, such as water vapor, whose source is also within the troposphere.

Atmospheric Gravity Waves

Energy transfer processes between the tropopause and stratosphere, as well as between high and low latitudes, are not well understood. It is known, however, that thunderstorms can generate gravity waves that may be important in these energy transfer processes [Stull, 1976; Balachandran, 1980; Larsen et al., 1982]. A geoelectric index derived from some of the observations discussed below could give extensive information on the intensity of global thunderstorms as a source for gravity waves. Some techniques (e.g.,

Schumann resonances) will give source location information as well. Space-based optical and infrared measurements of cloud cover and cloud top temperature are often insufficient to identify individual thunderstorms because individual thunderstorms are usually smaller than the satellite resolution grid size. Even if the National Aeronautics and Space Administration (NASA) plans for a satellite lightning mapper (H. Christian, NASA/Marshall Space Flight Center, Huntsville, Ala.; private communication, 1985) are realized, we will still not have global lightning coverage without three geostationary satellites. Much of the information needed to quantify this important source of gravity waves could be available from a ground-based system of measurements (as discussed below) of the type that are necessary for a geoelectric index.

Meteorology: Fog Forecasting

Earlier this century, there was considerable optimism that atmospheric electrical measurements would be useful for meteorological forecasting [Chalmers, 1967]. After all, the atmospheric electric field was known to respond to a large number of meteorological effects, such as winds, storms, chemistry, and humidity. Unfortunately, it has not turned out that way so far because sorting out the cause of each of these electric perturbations has proved nearly impossible. Here we will give just one example of how a geoelectric index might help fog forecasting.

Lower atmospheric conductivity is dominated by small ions that tend to be hydrated with weakly bound water molecules. The mobility of these ions drops drastically as the ions attach to aerosols, thus reducing conductivity. Atmospheric conductivity might then be useful in forecasting fog formation and dissipation [see Israel, 1973]. This has been studied most extensively by a group at the Naval Research Laboratory (Washington, D.C.), who report that by using both atmospheric electric conductivity and electric field measurements along with a list of empirical forecasting rules, one can forecast both the formation and dissipation of fog to better than 80% time [Anderson and Trent, 1966] for certain sites. Forecasting fog with conductivity measurements alone was found to be unsuccessful in polluted air [Ottevanger, 1972]. Nevertheless, the great financial losses due to fog closures at airports are a strong argument for renewed efforts to improve fog forecasting. Long-term uncertainty about fog increases air transportation costs because airplanes must carry extra fuel for alternate landing sites, but the highest costs are incurred while the airport is closed while waiting for fog to lift. Thus better short-term fog dissipation forecasts are perhaps even more financially important.

As haze and fog increase, resulting in decreased conductivity, the electric field is also strongly influenced. This is easiest to understand simply as a constant current phenomenon if the global current as well as the local columnar resistance remain relatively unaffected. If the current density remains constant but the conductivity decreases, then Ohm's Law requires an increase in the electric field. Therefore, to help separate variations in global current sources from the local fog effects, we need to know what the global circuit is doing. Furthermore, use of any other atmospheric electrical information to help

predict other types of local or regional weather and climate variations will also require separation of global from local influences.

Possible Methods for Deriving a Geoelectric Index

We know how to make electric field, current density, and conductivity measurements in essentially any fair weather environment, from the earth's surface to the solar wind. We also know how to make remote sensing measurements that are related to thunderstorms and lightning, again from both ground-based and space-based platforms. The direct in situ electrical measurements are the only ones that are direct measures of the current flowing in the global circuit. On the other hand, at any single measuring site it is difficult to separate local variations from global ones without multiple remote locations. Therefore, in addition to reviewing how we might construct a geoelectric index from in situ electrical measurements, we will also investigate the possibility of using other measurements related to remote sensing of thunderstorms or lightning.

In Situ Electrical Measurement Techniques

We can measure the various parameters of the global electric circuit within the fair weather regions outside thunderstorm areas, such as the vertical electric field E_z , the vertical electric current density j_z , and the electric conductivity σ . From Ohm's law, we determine the relationship

$$j_z = \sigma E_z \quad (1)$$

and the electric potential $\Phi(z)$ between the surface at a height z_0 above sea level and source height z is

$$\Phi(z) = \int_{z_0}^z E_z dz = Rj \quad (2)$$

where

$$R = \int_{z_0}^z (dz/\sigma) \quad (3)$$

is the columnar resistance between z_0 and z , and j is the average current density within the column.

Now, the electric conductivity within the atmospheric boundary layer is subject to considerable variation due to natural and man-made pollution. Often, what is measured on the ground is the local weather and/or man-made pollution. Only from ocean stations and from remote arctic and antarctic stations do we expect to obtain data of the electric field (for example) that reflect the true global behavior of the electric fair weather field. Airplane [Markson, 1969] or balloon measurements of the electric field outside the mixed layer (about 1 km above the ground) and, in particular, balloon measurements at stratospheric heights at constant density levels [Holzworth et al., 1984] appear to provide such "clean" behavior of E_z .

The electric potential $\Phi(z)$ can be measured with soundings from either balloons or aircraft up to heights near 10 km (or above), from which we may derive the ionospheric potential $\Phi_\infty = \Phi(z \rightarrow \infty)$. At 10 km altitude, 90% of this total potential has been reached. It depends on the properties of the sources—the thunderstorms—whether Φ_∞ or $j_G = (j)_{\text{global}}$ will truly reflect the variability of the sources. If the thunderstorms are currents

sources as suggested by most observations, then j_G is expected to be proportional to these sources. However, if they are voltage sources, then Φ_∞ should be proportional to them. Solar activity may modulate not only the fair weather total columnar resistance R [Hays and Roble, 1979] but also the resistance R_z between the tropopause and the ionosphere [Markson, 1969; Holzworth and Mozer, 1979b], and this may influence the efficiency of the sources that generate the global electric circuit. Furthermore, most of these techniques are labor intensive (involving factors such as frequent airborne or balloon soundings to obtain Φ_∞), except, perhaps, for the long-duration balloon techniques.

Remote Sensing of the Source Properties

Cloud pictures from satellites provide immediate information about global storm activity. Unfortunately, a unique method to discriminate between electrically active and inactive clouds does not exist. Lightning detectors aboard satellites give direct information about thunderstorm activity [Orville and Spencer, 1979; Turman and Edgar, 1982]. However, at present no such satellite is in orbit or being built. Moreover, the ability to detect lightning from low earth orbit is limited by the orbit to only a small fraction of all strokes. Investigations are under way to allow construction of geostationary satellites with instruments of much higher sensitivity.

Ground-based measurements of thunderstorm activity use the electromagnetic pulses from return strokes (sferics) to locate active areas. Here it is possible to use a system of broadband receivers in the very low frequency (VLF) and low-frequency (LF) ranges to locate lightning events by the direction finding method. Relatively small base lengths of (at most) a few hundred kilometers are necessary to pin down single return strokes with an accuracy of a few kilometers. This method is therefore useful on the continents. However, a great number of simultaneously operating stations are needed to cover larger areas of a continent [e.g., Krider et al., 1980].

Single-station techniques to locate lightning have been developed in the VLF range [Volland et al., 1983] and in the VLF/extremely low frequency (ELF) range [Taylor and Sao, 1970]. These techniques allow the location of active areas at distances up to several thousand kilometers. However, the accuracy of these methods is limited to at most ~10% in distance measurements. Also, many sites would be required to cover the globe.

The most promising technique for monitoring the global variation of lightning events appears to be the use of Schumann resonances. The earth-ionospheric spherical capacitor has a fundamental cavity resonance (called the Schumann resonance) at about 7 Hz with a cavity $Q = 2$ or 3 [Polk, 1982]. Lightning currents are responsible for initiating the cavity resonance. Since this is a global resonance of the entire capacitor, even one site can yield useful global information on the sources. The measured power in the Schumann resonance lines is related to both the total global lightning current moment and the geometry that relates source and observer [Polk, 1982]. Kemp and Jones [1971] showed that a single measuring site can be used to determine the source-observer separation dis-

tance, and Polk [1982] discussed the monitoring of worldwide thunderstorm intensity. The measurement apparatus consists of two horizontal magnetic field antennas and a vertical electric field antenna that are monitored in the 3–50-Hz range. Up to seven or eight harmonics of the fundamental can be seen with the most modern observing apparatus (D. Sentman, Institute for Geophysics and Planetary Physics, University of California, Los Angeles; personal communication, 1985). Nodal points within the earth-ionospheric capacitor would require the use of more than one site, but we estimate that as few as three well placed Schumann resonance sites could give both the total global lightning current moment and the general location information of the activity centers. These sites can be operated remotely, with little or no human interaction required. The Schumann resonance technique could therefore be used to give a value that is directly related to the intensity of global lightning current. This could be a cost-effective, long-term alternative to the more labor intensive in situ techniques.

Recommendations

The necessity for simple, reproducible data that is continuously produced for a long time span and that gives information about global geoelectric activity with at least some discrimination of the sources eliminates immediately most of the possible methods outlined in the section above. Satellite-, balloon-, and aircraft-based measurements probably cannot be conducted routinely at several places on the earth without great expense. Of the ground-based measurements, only the multiple station techniques of lightning location and the Schumann resonance measurements are global in nature and allow a certain discrimination of local sources.

In this case, the measurements of the Schumann resonances are one of the most promising because they require the least data processing and the lowest number of sites. They are highly reproducible and provide global coverage. On the other hand, they allow a separation between source effects and wave propagation effects, and also allow users to discriminate the location of sources at least on a medium scale. Their sensitivity to local sources is limited. Certainly, fewer than six stations appropriately located on the earth would be sufficient to produce data useful for a geoelectric index. However, although promising, the Schumann resonance technique is only one of several possibilities of varying cost and complexity.

Conclusion

Discussions are going on about the introduction of a geoelectric index that should serve the scientific community in a manner similar to that of the solar sunspot number or the various geomagnetic indices. There was a special session at the 1986 AGU Spring Meeting in Baltimore, Md., on the subject. Also, Division 2 of the International Association of Geomagnetism and Aeronomy has a Working Group on Middle Atmospheric Electrodynamics (MAE), chaired by R. Goldberg, which set up a subcommittee in Hamburg, Federal Republic of Germany, in 1983 to discuss the question of a geoelectric index. H. Volland (one of the authors of this paper) is the chair-

man of this subcommittee. In this article, we have outlined some basic ideas, partly coming from discussions with this subcommittee and the AGU CASE (Committee on Atmospheric and Space Electricity) standing committee. We hope to obtain suggestions from a wider audience interested in the subject of atmospheric electricity so that we—as a discipline—can proceed in reaching a final conclusion. In our opinion, the answer to the question posed by the title is a resounding *yes!*—and the sooner the better.

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Stratospheric Conductivity Variations Over Thunderstorms

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This paper reports the first in-situ observation of variations in the electrical conductivity over thunderstorms at 26 km altitude. The vector electric field, positive and negative polar conductivity, and optical lightning power/flash were measured by payloads on superpressure balloons in the southern hemisphere in early 1984. We find that in 72% of the thunderstorm periods observed (or in 23 of 32 periods) there were clear cases of conductivity variations while the balloons were over the thunderstorms. We present examples from two separate balloons at widely separated dates and locations showing both daytime and nighttime events. The conductivity measurements are made with the relaxation technique, and the vector field measurements are based on the double Langmuir probe high-impedance method. We find that the positive and negative conductivity measurements vary independently and have a different temporal profile than the dc electric field. The polar conductivity variations can exceed a factor of 2 at this altitude. In seven of the nine most intense thunderstorm events the total conductivity increased, while in only one of these nine events did it decrease (one event had no change). Implications of these observations for global current patterns are discussed.

INTRODUCTION

Stergis et al. [1957] reported stratospheric conductivity measurements of less than 1 hour from each of three balloon flights over Florida thunderstorms. Their conductivity measurements were indistinguishable from the conductivity on the sides of the storms. Subsequently, several researchers have made electrical measurements over thunderstorms [cf. *Mozzer*, 1971; *Benbrook et al.*, 1974; *Bering et al.*, 1980; *Holzworth*, 1981] which included no more than a hint that the electrical conductivity over thunderstorms might be affected by the presence of the storm itself. In this paper we report many cases of marked conductivity variations over thunderstorms, in apparent contradiction to these earlier reports. We will show that in some cases the positive and negative polar conductivity at 26 km altitude vary independently by over a factor of 2. In this data set, such large variations are never seen except near thunderstorms. These observations have important implications for our understanding of local and global electric current flow from the thunderstorm source. All of the direct thunderstorm models [cf. *Holzer and Saxon*, 1952; *Park and Dejnakintra*, 1973] as well as all the models of the large scale current systems associated with thunderstorms [e.g., *Hays and Roble*, 1979; *Kasemir*, 1977; *Hale*, 1983; *Makino and Ogawa*, 1985; *Tzur and Roble*, 1985], use fair-weather conductivity profiles above the storms to map the electric current driven by the thunderstorm to the global environment. The data presented herein add another variable to the problem so that one can no longer justifiably assume that all variations in global (or large scale) current systems are due to source variations (for example, number and location of worldwide thunderstorms).

In this experiment, eight superpressure balloons were launched from Christchurch, New Zealand, in 1983 and 1984, which resulted in over 180 payload days of electrical parameter

measurements. The Electrodynamics of the Middle Atmosphere experiment (EMA) was sponsored by the National Science Foundation and NASA and has been described by *Holzworth* [1983]. In our data set we have identified 23 thunderstorm or electrified cloud encounters wherein the conductivity at 26 km was different than the nearby fair weather conductivity. In this paper we will present two representative cases of different location, local time and month. The main points to be made include: (1) a demonstration that our payloads were indeed over thunderstorms; (2) proof that our instrumentation was operating properly (including a full discussion of possible errors); (3) a demonstration that both polarities of polar conductivity did in fact vary by up to factors of 2 over these storms; and (4) a discussion of some possible implications for models of global current flow.

DATA SET

The data to be presented in this report include vector electric field measurements, positive and negative relaxation time constants (and therefore both polarities of polar conductivity), and the optical lightning flash rate and intensity. A simple description of the electric field and conductivity measurements in the EMA experiment was presented by *Holzworth et al.*, [1984] in a discussion on another topic. Orthogonal pairs of isolated, Aquadag-coated, spherical conductors were used to determine the vector electric field using the double-Langmuir probe technique of *Mozzer and Serlin* [1969] and *Holzworth* [1977]. In this experiment the probes were 15-cm radius aluminum spheres with a capacitance of about 16 pF. Input impedances to the electronic circuits were measured to be higher than 4×10^{14} ohms, and active control of shielding voltages eliminates most extra stray capacitance [see *Holzworth*, 1977]. The method provides a measure of the three components of electric field to an accuracy of about 1 mV/m (horizontal components) and ± 15 mV/m for the vertical component. Both polarities of conductivity were measured by the relaxation time constant method. The relaxation time constant technique has been successfully used by many previous experimenters to determine stratospheric conductivity [*Mozzer and Ser-*

lin, 1969; Benbrook *et al.*, 1974; Bering *et al.*, 1980; Holzworth, 1981; D'Angelo *et al.*, 1982; Rosen *et al.*, 1982 and Holzworth *et al.*, 1985]. Benbrook *et al.* [1974] argued that the technique gives results "in excellent agreement with similar results reported by Paltridge *et al.* [1965]" who used the Gerdien condenser technique. In our experiment (τ_{\pm}) is determined by first biasing the upper and lower vertical conductors by +2.4 and -2.4 V respectively, and then floating the probes to determine the exponential time constant for return to ambient voltage [see Holzworth, 1981]. Simultaneous data from each probe are separately least squares fit to an exponential function and used to determine the conductivity $\sigma_{\text{(total)}} = \epsilon_0 (1/\tau_+ + 1/\tau_-)$, where ϵ_0 is the permittivity of free space. This calculation is performed by the on-board data system, and the results are telemetered with 10-min temporal resolution. Additionally, up to 24 times a day the actual high time resolution decay profiles from one polarity or the other (alternately) are telemetered, which allows careful checking to verify proper operation of the data system.

The lightning flash rate was continuously monitored in the optical spectrum by a Hewlett/Packard PIN photodiode. A simple threshold for transient rise time and amplitude is set, and the output feeds both a transient counter as well as a peak power detector. Unfortunately, the daytime background light effectively raised the threshold to the point that we recorded only five daytime lightning flashes in the entire data set. However, in darkness the detector worked properly and will be used here only as support for the conclusion, arrived at by looking at the vector electric field data, that the payloads were actually over thunderstorms. In addition to the flash count rate, the detector measured the peak optical power for the largest stroke in each 10-min interval. The power levels ranged from a threshold for counting of 5×10^8 W to our highest level, which included everything over 1.2×10^{10} W.

Figure 1 presents a typical, isolated, nighttime thunderstorm in which the vertical electric field obtains an inverted polarity (opposite to fair weather-direction) and, along with the horizontal component, exceeds a magnitude of a volt per meter. This magnitude is similar to the magnitudes over thunderstorms reported by Mozer [1971], Benbrook *et al.* [1974], Bering *et al.* [1980], Holzworth [1981], and Holzworth *et al.* [1985], but it is 2 orders of magnitude below that reported by Stergis *et al.* [1957]. In Figure 1, both the positive and negative polar conductivities are seen to vary by over a factor of 2. Note that prior to 1300 UT and following 1700 UT there are only minor conductivity fluctuations. A low level of apparently random conductivity fluctuations is always seen in fair weather, but the fluctuations rarely exceed 30% of the mean in either component and then only in response to a geophysical event (such as these thunderstorms, or a solar proton event). Thus large conductivity fluctuations such as those shown in the top two panels of Figure 1 are always uniquely associated with thunderstorms.

In Figure 1 there are times when no data are available for the following reasons. The on-board computation of the least squares fit to determine the exponential time constant was not able to process data exceeding a digitizing window of ± 5 V. Thus if the electric field was too high, the program would use incorrect data in the time constant determination. Since we also telemetered the vertical electric field on several gains, we are able to unambiguously remove these bad time constants. Also, if the ambient vertical electric field produced a floating probe voltage within 100 mV of the bias voltage (± 2.4 V), the exponential fit was inaccurate because of the finite size of the digitizing step, based on an eight-bit analog-to-digital converter. Therefore there are times when no data are available.

The data in Figure 1 come from payload EMA 8 on February 15, 1984, at 45.6° S, 150.8° E, and 26 km altitude. At the time of the thunderstorm in Figure 1, the payload was in darkness. The optical flash data are shown on the bottom panel. The instrument recorded 14 total flashes with peak power over our threshold with the maximum count in each 10-min period occurring at the same time as the peak in the vertical electric field. Furthermore, the peak intensity of any flash in each basic 10-min interval followed the same general pattern, with at least one flash with power above 1.2×10^{10} W (assuming it was located on the ground at nadir) simultaneous with the vertical electric field peak (actually above our digitization window) at about 1440 UT (see third panel from bottom in Figure 1). Thus for this nighttime event we can unambiguously say that the payload was indeed over a thunderstorm.

Figure 2 is another example of a typical thunderstorm encounter, as viewed electrically from the stratosphere. The data in Figure 2 come from a daytime event (and hence include no lightning flash data) from the payload EMA 6 at 44.7° S, 156.4° E. This storm occurred just after sunrise near the end of a very disturbed period extending back nearly 24 hours with multiple thunderstorm signatures. The event in Figure 2 was chosen to demonstrate the solution to some potential errors in this type of measurement. The data in Figure 2 are similar to those of Figure 1 in that the electric fields undergo the same general variations. For the time period of this event, however, we have access to high-resolution time-decay (i.e., relaxation time constant) data at the peak of the storm. Thus although the electric field exceeded the digitizing window amplitude, we have the actual data used by the on-board data system to calculate the exponential time constant. As in Figure 1, any time constants determined by the on-board computer when the electric fields were too high have been eliminated, except in the two cases discussed below when we telemetered the actual decay profile. The conductivity measurements near 2100 UT (triangles in panels 1 and 2, Figure 2) come from the data presented in Figure 3.

Figure 3 presents four time decay profiles. Each of the four curves shown in Figure 3 is the result of actively biasing the probes by ± 2.4 V and then letting them refloat. An exponential curve is then least squares fit to the data, resulting in a time constant determination which is inversely proportional to the polar conductivity. In Figure 3, the upper panel traces are from times just prior to the thunderstorm shown in Figure 2 (i.e., in otherwise fair weather), while profiles in the lower panel are taken just at the peak of one of the events in Figure 2 (see triangles). Note that while the on-board computer conducts both time constant measurements simultaneously every 10 min., the high-resolution data for only one polarity is available at a time because of telemetry limitations. Thus every 10 min, along with the on-board-calculated exponential fits, only one of the actual decay profiles is added to the real time telemetry, which is then in turn only available when the satellite is over the balloon, usually 12 to 18 times per day. The lower two panels are the only real time data available during thunderstorms when the conductivity was perturbed. In three other cases, real time decay profiles were available when the electric field indicated we were near a thunderstorm, but the times of those data did not correspond to the times of the conductivity variations (and in fact those decay profiles agreed with the fair-weather values). In the lower panel of Figure 3 the vertical electric field was larger than the analog-to-digital (A-to-D) voltage window. (Note that the A-to-D maximum voltage of -5 to +5 V and with the electronic gain of one-half the peak values of electric field reported corresponds to an electric field of 6.67 V/m when divided by the 1.5-m boom length).

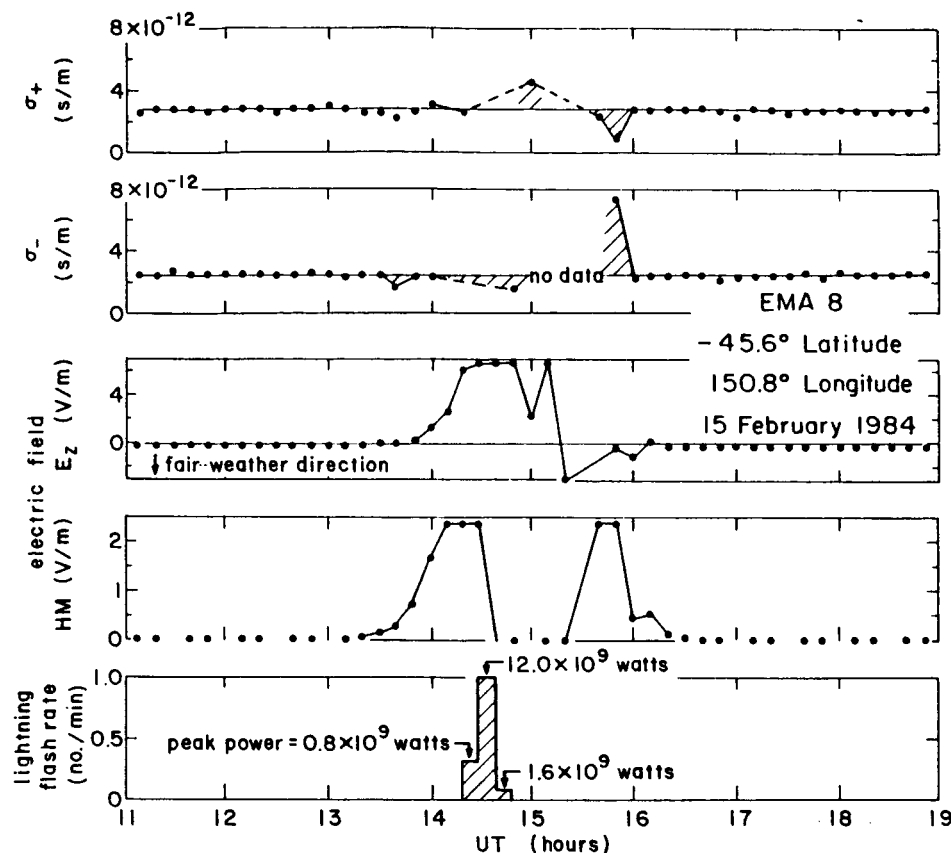


Fig. 1. Ten-minute averages from 8 hours of stratospheric data at night near a thunderstorm. Positive and negative polar conductivity using relaxation techniques are given in the top two panels. Vertical and horizontal electric fields indicate that a thunderstorm occurred between 1300 and 1650 UT. Optical flash counter indicates lightning at the peak of the storm.

There are three important points to note about Figure 3. First, although the floating voltage of each probe is beyond the window maximum, it is still possible to evaluate the decay time constant by least squares fitting a function of the form $V = a + be^{ct}$ to the voltage data V , where t is the time and a , b and c are constants determined by the fit. Thus only four data points in the decay curve are required to make this best fit (one more than the number of degrees of freedom), which determines both the exponential time constant $\tau = 1/c$ as well as the baseline voltage level a . Since more than the minimum four points are available in all cases shown, and the data are relatively smoothly varying, the fits have generally very good correlation coefficients ($r^2 > 0.998$ in all cases). Thus we not only determine the actual time constant at the peak of this event but also obtain a value for the dc electric field, which would not have been available without the high time resolution data. In other words, by determining the level of the vertical field from the fit to the decay curve as above, we not only obtain a value for conductivity but also know that the instrument was in an electric field environment which (even though out of the data-digitizing window) would not harm the electronics.

The second point to note about the decay curves in Figure 3 is that during the times of large fields, the probes collect ions of the opposite sign to ions collected during fair weather. These passive spherical probes do not emit any charge. We use simple passive conductors which allow ample time resolution for determining electric fields at these altitudes, where the conductivity is typically a couple of orders of magnitude larger than at the earth's surface. Thus when a probe is allowed to float electrically, it col-

lects charge of only one sign, depending on whether it was previously biased positively or negatively with respect to the floating voltage. Normally, with fair-weather fields near 300-500 mV/m (see upper panel, Figure 3), biasing a probe by ± 2.4 V will result in ion collection of negative or positive charge, respectively. However, in the case of the lower panel, the floating voltages are above (or below) the bias voltage and thus ions of the sign exactly opposite to the normal sign for that probe are collected. This point is taken into consideration in the plots of positive and negative conductivity in Figure 2 (triangles).

The third major point to be made from Figure 3 is that the decay time constants are in fact determined from clean data, which are not perturbed by lightning transients. A major potential criticism of the measurement of conductivity by the relaxation technique over thunderstorms is that lightning occurring in the midst of the decay time profile could cause a non monotonic decay profile due to a voltage transient. In turn, that could cause completely erroneous interpretation of the least squares coefficient data if only the fit results were available, without the raw decay profiles. In fact, we have seen at least one example in which the decay profile was disturbed by an apparent lightning transient (similar to those described by Holzworth [1981], Holzworth and Chiu [1982] and Holzworth et al. [1985]). Thus it is possible that some of the conductivity variations presented in Figures 1 and 2 are affected by lightning transients, and it is only in the cases such as shown in Figures 2 and 3, when we actually have real time data that we can be sure this did not happen. On the other hand, we will argue that often the disturbed time

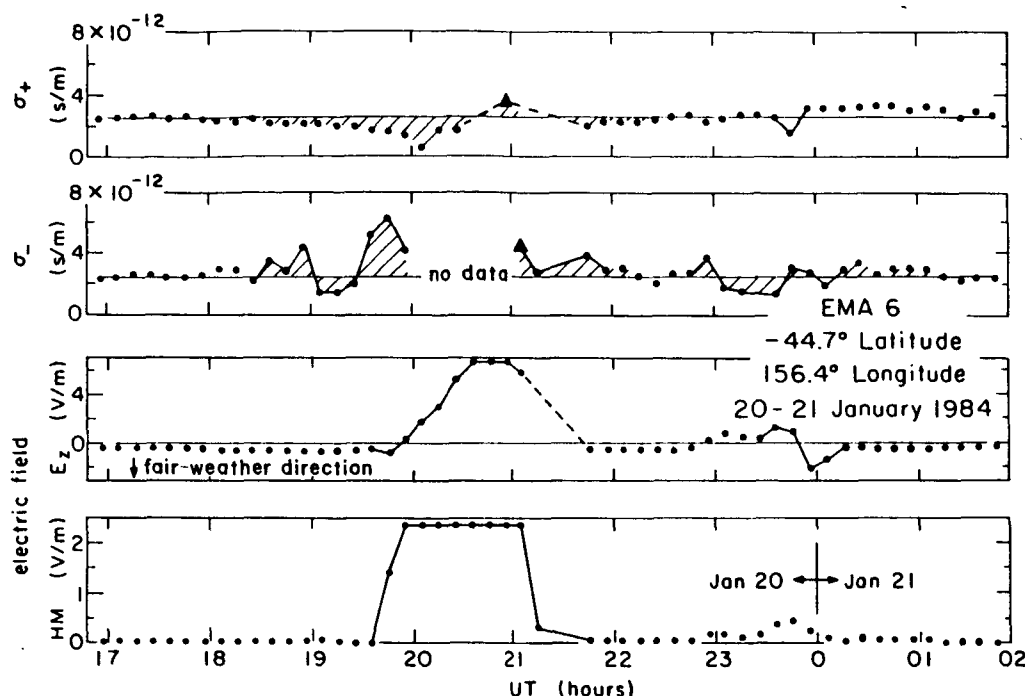


Fig. 2. As for Figure 1 (except that no optical flash data were available), from a different payload for a daytime thunderstorm.

conductivity measurements are reasonably smoothly varying (e.g., near 1900 UT in Figure 2) over times of tens of minutes, which would be very difficult to explain as simply a series of misappropriately placed lightning transients in an otherwise fair-weather conductivity medium.

Some further points concerning error analysis are worth reporting. In the first two payloads flown (EMA 1 and EMA 2) we used bias voltages of +5.5 and -5.5 V for the upper and lower spheres. We were worried that this might be too large a potential difference to be certain we were still in the linear region of the current-voltage profile so we reduced the bias voltages in the last six flights to ± 2.4 V. As far as we can tell, this instrumental difference itself resulted in no change in the measured average fair-weather conductivity measurements. Thus at least up to a total potential difference of 5.5 V, the relaxation time constant measurement collects ions at a rate linearly dependent on the voltage (i.e., we have not depleted the ambient ionic number density in the volume of air near the probe which would result in a non-linear current-to-voltage curve).

In an effort to see if there were unknown payload effects perturbing the conductivity time constants due for example to the probe geometry, we reversed the polarity of the bias voltages on different payloads so we did not always bias the upper vertical probe positively and the lower one negatively. Thus, both upper and lower probes were used to determine both polarities of the conductivity at times during the series of flights. Again, we could find no differences in the conductivity due to this polarity alteration. This was true even in the case when two balloons were up and "nearby" (within 400 km) with oppositely biased conductivity probes, but we found the fair-weather positive and negative conductivities were in complete agreement. We even radically modified one payload ground plane by introducing a large conducting cylinder around the entire payload, with no apparent effect on the measured fields or conductivity (indicating that the usual ground plane defined by rectangular plates on the four vertical faces of the payload was sufficient).

With regard to the real time measurements of the conductivity decay time profiles shown in Figure 3, it should also be noted that we performed fits of the exponential function for nearly all the fair-weather data, with the result that the floating potential determined by parameter a in the fit was very near the actual floating voltage.

A potential criticism of the relaxation time constant method in general is that the ion density in the vicinity of the probe may be affected by an "electrode effect" [Israel, 1971]. When a conductor is biased with a voltage much different than that of the ambient air, ions with the sign of the biasing charge are repelled from the vicinity of the probe thus depleting the ion density of that sign. This can be a severe problem with this type of measurement near the earth's surface in fields of the order of 100 V/m and still air. We do not believe this is a problem in the stratosphere on these balloons for the following reasons. First, there appears always to be a flow of fresh air in the vicinity of these balloon payloads. This has been determined for these balloons in particular (Smalley, EMA Project Engineer, private communication, 1985) and for all superpressure balloons [Lally, 1975] in general. This air flow comes from a fundamental, undamped balloon buoyancy oscillation with a period of about 3 min and amplitude of ± 10 -20 m (average) and ± 50 m (peak) (see also Massman [1978]). Also, in the vicinity of the balloon there is a thermal column of air rising in the day and subsiding at night which has a measured flow of about 30 cm/s. Thus it appears likely that at nearly all times there is a combined flow of air in the vicinity of the balloon payload of a few tens of centimeters per second. This is enough to eliminate the possible disturbance [Israel, 1971, p.217]. Furthermore, if the electrode effect were indeed a problem, one might expect to find a highly variable conductivity, which is not the case for these measurements or those referred to above by other authors. Finally, we note in this regard that several bias voltages were used in the experiment. Primarily, the ± 2.4 V level was used, but the prototype flights used ± 5.6 V, and an earlier test flight of the payload on a zero-pressure balloon

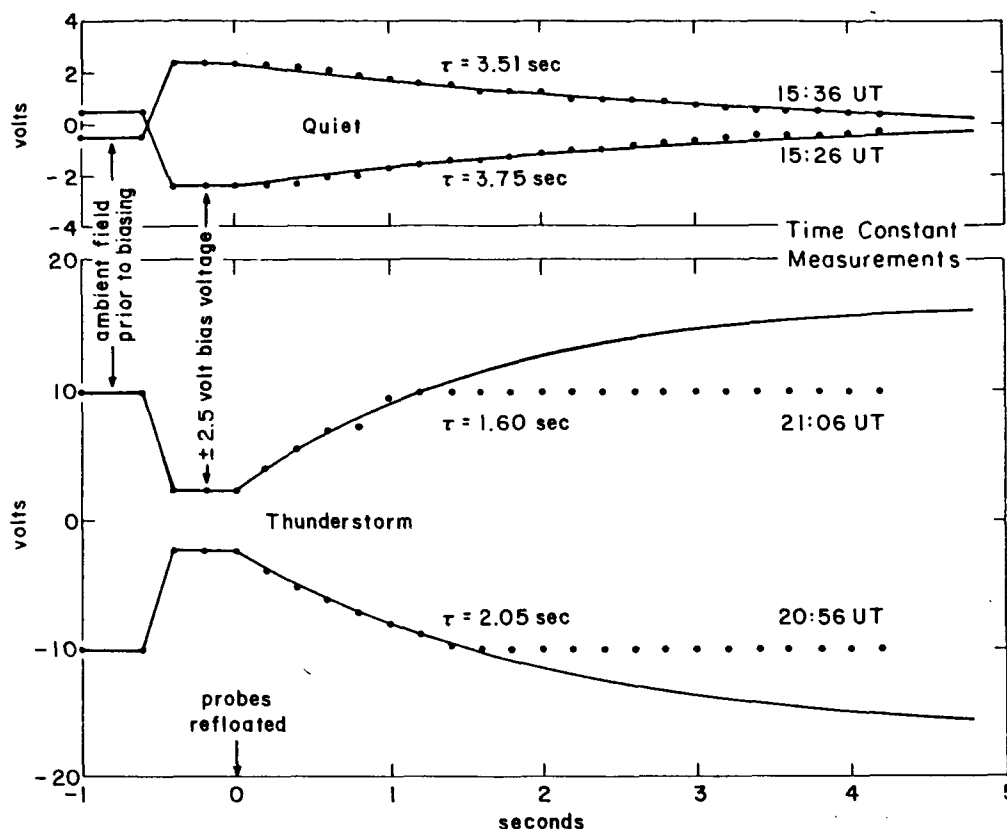


Fig. 3. Relaxation profiles (from biased voltage to floating voltage) to determine the conductivity (top) in fair weather and (bottom) over a thunderstorm. The lower two curves produced the data points indicated by triangles in Figure 2.

performed a bias voltage sweep between -2.5 V and $+2.5$ V over 10 s and found excellent linearity in conductivity determination. Thus we do not believe the electrode effect is a problem in the data reported in this paper.

A statistical survey of thunderstorms which were seen in our data set during January and February 1984 (the peak occurrence period in the southern hemisphere) was performed. During this period our data set included 59 payload days from five payloads on mid-latitude balloons (36° to 55° S latitude). During that time only one case of conductivity variation in fair weather was identified which occurred on Feb 16, 1984, just after a solar flare. This variation is the subject of another paper. This data sample included 154 hours from 32 separate storm periods during which the dc electric field as seen by a payload indicated the unambiguous presence of a thunderstorm. These thunderstorm periods ranged from single-celled thunderstorms of 1-hour duration to one period lasting over 12 hours with several identifiable cells. Of these 32 storm periods, all but nine (for a total of 72% of the cases) showed clear conductivity variations in at least one polar component at some time during the period. In all but the nine cases, at least one occurrence of non-fair-weather conductivity (defined to be more than 30% above or below the nearby conductivity on the sides of the storm) was measured. This is not as precise a definition as one might prefer as the basis for a statistical survey, but we have no information (other than the on-board measurements of electric field and lightning flash rate) as to the exact balloon positions relative to the storms. Therefore it was felt that to define occurrence in terms of percentage of time rather than percentage of storm periods would be misleading in other ways. Of the nine cases with no obvious conductivity variations, six were shorter than 3 hours each. All together the nine "no

effect" cases totaled 31 hours of the 154 storm hours, about 20%. None of these storms was simultaneously observed by two payloads.

During the January and February 1984 storm time data set discussed above, we identified nine intense storms, arbitrarily defined as storms with electric fields having interted vertical polarity with magnitudes above 1.67 V/m as well as a horizontal magnitude exceeding 0.470 V/m. Of these nine intense storms, six had a clear total conductivity increase, one a possible (but small) increase (i.e. one point), one showed no conductivity change, and one had a clear conductivity decrease. Thus in 78% of the intense storms a conductivity increase was apparent near the time of the height of the thunderstorm activity. These conductivity variations did not seem to be correlated in detail with the electric field values. By this we mean that while the thunderstorm periods (with associated electric field changes) are indeed associated with the conductivity variations, the maximum conductivity changes do not correlate with the exact time of peak electric field. This is clearly seen in Figure 1 where the largest conductivity variation occurs at 1550 UT when the electric field is still clearly perturbed by the storm but is nowhere near the instrument saturation level, as it is near 1430 UT.

DISCUSSION

In the plots and data discussed above we have shown that there are times when the conductivity over thunderstorms is different from the nearby fair-weather conductivity by as much as a factor of 2 at 26 km. The sense of the variations in these limited statistics can be in either direction, so we are prevented from making a sweeping statement about the opening or closing of a conducting "valve" between the thunderstorm and the

upper atmosphere. However, the conductivity over thunderstorms is anything but spatially constant at the fair-weather value. As noted above, we have several examples of times when the conductivity perturbations were very slight, if they existed at all, but the electric field still showed the clear signature of a thunderstorm. Note that the electric field measurements are a form of "remote sensing" of the thunderstorm, but the conductivity measurements are always in situ. Thus the lack of a one-to-one relationship between σ and E variations at 26 km does not mean that sometimes σ over the storm is not affected. We may just have missed it because of spatial or temporal effects. This experimental result complicates the interpretation of how electric currents, driven by potential differences developed inside thunderstorms, might couple to the upper atmosphere and ionosphere. By this analysis we argue that an invalid assumption about the conductivity is made in most models which predict thunderstorm current flow. The assumption that the conductivity in the stratosphere is constant, independent of the presence of the thunderstorm itself, may be incorrect.

We have considered several possible mechanisms to account for the observed conductivity variations but cannot point to one that is conclusively responsible. One possible cause which can be eliminated is vertical balloon motion. Since the fair-weather conductivity has an exponential altitude dependence [cf. Mozer, 1971; Holzworth *et al.*, 1985] any substantial vertical balloon motion would be visible in the conductivity. However, these superpressure balloons float on a constant density surface [Lally, 1975] and in this case were observed by radar to have less than 100 m variability in a day [Holzworth *et al.*, 1984]. Furthermore, onboard pressure sensors indicated no significant altitude variability during the times discussed here. Thus, balloon vertical motion cannot account for the observations. It is interesting to speculate as to why the earlier investigations did not show these effects. Primarily, all the previous balloons were of the zero-pressure type, which have little altitude stability. Many of the researchers (including this group) were familiar with observing conductivity changes due to altitude variations with amplitudes much larger than those reported herein. Therefore one might tend to overlook conductivity variations as small as 30%. Also, as seen in Figures 1 and 2, only a very few actual data points exceed the 50% (or factor of 2) level. Out of all our thunderstorm encounter time, the total data exceeding this level is at the 5% level. Thus the probability of having seen these types of variations in the total data sets of the earlier investigations is quite small, since all those flights were very short compared to these superpressure balloon flights.

Speculation as to the possible mechanism for a conductivity variation over thunderstorms is probably premature at this time. We suggest only that more experiments using different techniques should be conducted.

Independent of the detailed mechanism, it is interesting to ask what is the logical implication of a factor of 2 change in conductivity over the thunderstorm? First, there is the obvious problem this implies for the assumption of spatial uniformity of the isotropic conductivity. Thunderstorm dc currents might be "channeled" in columns which are physically quite different from those inferred by simply assuming an exponentially increasing uniform conductivity. Of course, if the conductivity was a factor of 2 higher or lower at all altitudes, the coupling to the ionosphere would not be affected because only the scale height of the conductivity enters the problem [cf. Park and Dejnakintra, 1973]. However, we do not believe this is a reasonable

interpretation of our single height measurements. The conductivity over the storm is likely to be related to the proximity of the storm itself. In this event the conductivity must eventually return to ambient values at some other altitudes. This would result in an effective change in the scale height of the exponentially increasing conductivity. Furthermore, the effect might be larger closer to the cloud in the very region in which the columnar resistance per unit altitude to upward current conduction is largest. In other words, changes in the conductivity between cloud top and our altitude of 26 km might play the role of a very sensitive controlling agent for coupling of the current from thunderstorms to the global circuit. It is possible that this effect could completely mask a 10-30% effect on the electrical coupling to the global circuit due, for instance to cosmic ray variations in the fair weather conductivity as discussed by Hays and Roble [1979].

It is perhaps too speculative to spend much effort with detailed recalculations of the coupling of thunderstorms to the upper atmosphere, based on our single-altitude measurements. Indeed, we do not know if the effect is larger above 26 km or below. Thus we cannot calculate the effect on the total columnar resistance between cloud top and, say, the ionosphere. However, we would like to point out that this effect is seen in the lower part of the circuit where the total resistance per columnar meter of altitude is likely to be much larger than at significantly higher altitudes where the conductivity is of course greatly increased.

CONCLUSIONS

We have studied electric field and conductivity data from eight separate balloon payloads in the stratosphere at 26 km altitude and have found that the electric polar conductivities over thunderstorms, as detected by the relaxation technique, can be quite variable. In 78% of nine cases of particularly intense storms, the total conductivity increased at some point over the storm. We have presented various arguments to show that our instruments were working and that we were actually over thunderstorms. The implications for coupling between thunderstorms and the global environment can only be speculated upon but are argued to be quite important. These measurements introduce yet another variable to the problem of electric field coupling. This new effect could completely mask small variations in current flow thought by some to be important to the problem of solar-terrestrial coupling.

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Global Circuit Variability From Multiple Stratospheric Electrical Measurements

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In this paper we have examined the vertical component of the electric field, conductivity, and the derived current density from eight superpressure balloons. Special emphasis was placed on the fair-weather, simultaneous measurements from widely spaced constant-altitude (26 km) balloons. The conductivity measurements were well organized by a simple ionization rate parameterization depending on the geomagnetic latitude. The variability of all the electrical parameters was found to be independent of the balloon separation. Much of the time the current density measurements were within 20%, for simultaneous flights, even though the balloons were up to 6000 km apart. Also, these simultaneous current density data show that the global current source was significantly variable on hourly and daily time scales. Finally, the use of the simultaneous current density data are discussed as a possible "geoelectric index." Advantages and limitations of such an index are discussed.

1. INTRODUCTION

In March 1983 and December 1983 through March 1984, eight superpressure balloons were launched from Christchurch, New Zealand, to measure the stratospheric vector electric field, polar conductivity, optical lightning flash rate, and vector magnetic field at an altitude of 26 km. These balloons were part of the Electrodynamics of the Middle Atmosphere (EMA) project [Holzworth, 1983]. These flights yielded over 4320 hours of data, resulting in one of the largest stratospheric vector electric field data sets. In a preliminary analysis of the first two flights, Holzworth *et al.* [1984] noted the simultaneous fair-weather vertical components of the electric field from both balloons were often within 10% of each other. Also, the diurnal mean field, from data averaged over many days, was similar to, yet not exactly like, the Carnegie curve. The main conclusion of Holzworth *et al.* [1984] was that there appeared to be a source variability on time scales faster than a diurnal basis. Thus the simple land-mass-thunderstorm explanation [cf. Whipple and Scrase, 1936] for the global circuit variability is not sufficient for the global circuit variability is not sufficient for describing the daily fair-weather electric field. In this paper we extend and expand the analysis of the constant-altitude electric field and relaxation time-constant (for conductivity) measurements for all eight flights. Data and error analysis, temporal and spatial variability of the vertical component of the electric field, conductivity, and derived vertical component of the current density are considered.

2. DATA SET

The eight superpressure balloons accumulated over 180 payload days of electric field and relaxation time-constant data. Figure 1 shows the trajectories of the balloons about the southern hemisphere. The first two flights, launched in March 1983, floated east over the Pacific Ocean toward South America, while flights 3 through 8, launched from December 1983 to February 1984, headed west past Australia. Most of the balloons stayed between -35° and -50° latitude. However, flight 3 spent many days in the full sunlit polar regions (below -60° latitude). The balloon

Fig 1

trajectories were such that data are available for a full 360° of longitude, primarily from middle latitudes. There were limited times when a few of the balloons did cross over land (southern parts of Australia and South America), but the majority of the data are oceanic. The flight times of each balloon are displayed in Figure 2. The white gaps are times when no data were available from the satellite data collection facility. The balloons typically stayed aloft 10-32 days at an altitude of 26 km. About 50% of the time there were two or more balloons simultaneously aloft. The separation of balloons ranged from 200 to 6500 km.

Fig 2

This paper will concentrate only on the constant-altitude data. Three balloons (3, 4, and 6) experienced a loss of superpressure at night during part of their flights. This loss of superpressure caused vertical motions easily identified by rapid changes in pressure, temperature, electric field, and conductivity. Therefore this study is limited to the remaining constant-altitude flights (1, 2, 5, 7, 8). The arrows on Figure 2 indicate when the loss of superpressure was first noted. This was not as restricting as it might appear, since heavy thunderstorm activity, especially during flight 4, already limited the amount of simultaneous fair-weather data. The nonsuperpressure data (altitude variation data) will be considered in later analysis.

3. CONDUCTIVITY

Conductivity was derived from measured time-constants, using the "relaxation" method. This technique has been widely used in the past by many experimenters [Mozer and Serlin, 1969; Benbrook et al., 1974; Bering et al., 1980; Holzworth, 1981; D'Angelo et al., 1982; Rosen et al., 1982], and, most recently, by Holzworth et al. [1986]. By biasing the upper and lower probes to an equal and opposite voltage (5.5 V for flights 1 and 2, and 2.4 V for flights 3 through 8), and then allowing the probes to return to their floating value, the exponential relaxation time-constant τ was determined. The probes were made of an "Aquadag" coated aluminum sphere which did not emit space charge; thus the time-constant measured was only for one sign of the charge carrier. The probes were each on booms, which were 1.5 m from the main payload and 3 m from tip to tip. The main payload itself was hung on a rope about 20 m below the superpressure balloon. If the bias voltage was larger (i.e., more positive) than the floating probe voltage, negative charge was collected; if the bias voltage was less than the floating voltage, then positive charge carriers were collected. The positive and negative time-constants were measured simultaneously every 10 min. The sign of the bias voltage for each probe was switched between upper and lower probes on alternate balloons. In other words, if the upper probe was biased with +2.4 V on one payload, then on the next balloon launched, the upper probe was biased -2.4 V. Thus both upper and lower probes measured time-constants of both charge carriers. The on-board data system fitted a least squares exponential curve to the decay data [Powell, 1983], from which a characteristic relaxation time τ_z was determined. Both time-constants and the actual high-resolution decay profile data were relayed when the Tiros satellite passed overhead. The high time resolution data were then available for verifying proper instrument operation. From

the relaxation time-constants, the polar conductivity is found to be

$$\sigma_{\pm} = \epsilon_0 (1/\tau_{\pm}) \quad (1)$$

where σ is the polar conductivity, ϵ_0 is the permittivity of free space, and τ is the measured relaxation time-constant. The total conductivity is the sum of the positive and negative polar conductivities.

There was one conductivity problem that has been diagnosed as an instrumental effect and eliminated from the data set. In all of the flights' conductivity measurements there was an apparent daytime increase that began about 3 hours after sunrise, peaked at local noon, and disappeared about 3 hours before sunset. This enhancement was not followed by the electric field. Although the source of this enhancement was not known, sun sensors and the thermal housekeeping data on the balloon suggested that the conductivity enhancement was a function of the sun angle. It should be emphasized that at night the conductivity measurements were very stable and slowly varying. Also, the nighttime conductivities from different balloons were in excellent agreement. For this analysis the enhancement was removed by subtracting the daytime values from a smoothly varying fitted curve. The resulting values were then added to a least squares fit derived from the nighttime data. Only the daytime conductivity values were affected, and the nighttime conductivity data remained untouched. This approach maintained most of the short-term variability of the daytime conductivity, which was important when the current density was determined (see later discussion). Although this method does put some uncertainty into the daytime values, the uncertainty is less than that from a smoothed fit using only the nighttime data. Also, a smoothed fit would also affect the entire data set. Only for the magnetic latitudinal comparison (discussed later) were the data smoothed, since the short-term variability (less than an hour) was not under investigation.

Figures 3a and 3b show 5 days of smoothed polar conductivity data from the March 1983 and December 1983 to February 1984 flights, respectively. In all flights the positive polar conductivities were larger than the negative polar conductivities. Other experimenters have observed one polar conductivity to be larger than the other [Paltridge, 1965; Reiter, 1977; Gringel et al., 1986]. The positive polar conductivities of flights 1 and 2, flown in March 1983, were about twice the negative values, while the positive polar conductivities of flights 3 through 8, flown over 9 months later, were only 10 to 20% larger. The magnitude of the negative polar conductivity was approximately the same for all flights, after accounting for the balloon's magnetic latitude (described later). The total conductivity was the sum of the two polar conductivities; typical values ranged from 3.8×10^{-12} to $6.0 \times 10^{-12} \text{ s m}^{-1}$.

In a recent article, Holzworth et al. [1986] examined in detail the error analysis of the EMA (nighttime) conductivity measurements. Therefore we will only briefly discuss the measurements here. To account for possible unknown geometry effects, the sign of the bias voltage is switched between the upper and lower probes every flight, as described previously. Thus each probe orientation was used to measure both positive and negative polar

Fig 3

conductivity on alternating flights by using different bias voltages. Also, the ground plane geometry of flight 4 was radically altered [see *Holzworth et al.*, 1986] without any apparent change in the measured conductivity values. In each of the two sets of flights, σ_+ was always greater than σ_- and the values for each σ (either positive or negative) were approximately the same (after accounting for the latitudinal variation). The difference in the positive polar conductivity between the March 1983 and December 1983 to March 1984 flights was not due to the difference in the bias voltage. We know this for a couple of reasons. First, the time-constant determined as the voltage drops from 5.5 to 2.5 V is the same as that determined from the data between 2.5 V and floating. Second, the floating voltage often changed (as near thunderstorms) without corresponding changes in the conductivity. As mentioned previously, it was the decay of the difference between the bias and floating voltages which determined the time-constant. Although the bias voltage was fixed, the floating probe voltage changed in response to the environmental potential gradient. Thus both sets of flights (1-2 and 3-8) at some time used the same bias-to-floating voltage difference to measure the positive time-constant and obtained results consistent with each set's time-constant measurements. In other words, the positive time-constant measured by the first set of balloons was half that of the time-constants measured by the second set of balloons, even though the bias-to-floating voltage difference used was the same. Also, there were many times during each thunderstorm when large thunderstorm electric fields were observed at the balloon, thus producing bias-to-floating voltage differences much larger than are seen in fair weather, with no corresponding change in conductivity [see *Holzworth et al.*, 1986]. It then follows that the factor of 2 difference in the bias voltage between the March 1983 and the December 1983 to February 1984 flights could not have accounted for the factor of 2 difference in the measured positive time-constants. We conclude that the difference in the positive conductivity between the two sets of flights is real and not instrumental.

The long-term variability, of the order of days, in the total conductivity can be attributed to the balloon's geomagnetic latitude, as shown in Figure 4. The earth's magnetic field deflects the incoming cosmic rays, so only the most energetic galactic cosmic rays can penetrate the equatorial regions. The less-energetic cosmic rays can reach only the more polar magnetic latitudes. As a result, the ionization rate toward the poles at any altitude is larger than the equator. This has long been known [*Hatakeyama*, 1965; *Heaps*, 1978] and incorporated in models of the global circuit [*Hays and Roble*, 1979; *Makino and Ogawa*, 1985]. The conductivity, to first order, is proportional to the square root of the ionization rate [*Israel*, 1971]. The cosmic ray cutoff, and hence ionization rate, can be parameterized by a $\sin^4 \lambda$ dependence [*Heaps*, 1978]. Thus the conductivity could be approximated by

$$\sigma = (A+B \sin^4 \lambda)^{\frac{1}{2}} \quad (2)$$

where A and B are constants, and λ is the geomagnetic latitude. Certainly, the conductivity-ionization rate relation is much more

Fig 4

complex than described above, but this parameterization is sufficient for showing the clear latitudinal dependence of the conductivity. The curves in Figure 4 are a least squares fit to (2) for each set of balloons. The curves fit the data reasonably well ($r = 0.94$ for flights 1 and 2; $r = 0.97$ for flights 5, 7, and 8). There are two curves related to the fact that flights 1-2 occurred 9 months before the second set of flights and that they each sampled separate regions of the southern hemisphere (see Figure 1). Thus the main variations in conductivity for any given flight are due to changes in the balloon's position with respect to geomagnetic latitude.

4. VERTICAL COMPONENT OF THE ELECTRIC FIELD

The vector electric field was measured using the double-Langmuir-probe technique of *Mozar and Serlin* [1969] and *Holzworth* [1977]. One pair of probes was oriented vertically along the rotation axis and the other two pairs were in the horizontal plane. These probes were connected to high-impedance, ultra-low-leakage differential electrometers. This method provides an accuracy of 1 mV m^{-1} for the horizontal components of the electric field and 15 mV m^{-1} for the vertical component [see *Holzworth*, 1977]. The electric field was sampled and averaged for each 10-min period by the on-board data system. As with the conductivity measurements, high time resolution (5-s sample rate) electric field measurements were relayed, typically 18 times a day, depending on the number of satellite passes, for verification purposes.

In fair weather the vertical component of the electric field was a couple of orders of magnitude larger than the horizontal component. In other words, the vector electric field was essentially vertical and pointing downward toward the ocean. Therefore we used the vertical component of the electric field E_z in place of the vector electric field in this analysis. A correction to E_z has been made for flights 3 through 8. There was a small step function decrease (0.104 V m^{-1}) in E_z occurring at sunrise and ending at sunset. The shift, possibly due to charging a VLF antenna (added to flights 3-8 only), was nearly constant every day for every flight affected. Whether this is a real variation or not has not been determined, but since it was easily fit by a small step function (the same step function for all affected payloads) it has been removed from the electric field for this analysis.

Figures 5a and 5b display the simultaneous E_z values of flights 1 and 2 and flights 7 and 8, respectively, for 5-day periods. Note that the polarity is negative, since the electric field is plotted rather than the potential gradient. Flights 1 and 2 are about 2000 km apart, while flights 7 and 8 are approximately 6000 km apart. The mean value for E_z was about -0.5 V m^{-1} (positive being in the upward direction). Thunderstorm times for single flights are indicated, and those data were removed. Thunderstorms can generally be identified by a vertical component of the electric field of inverted polarity (from fair weather) and a 1-3 order of magnitude increase in the horizontal component of the electric field [see *Holzworth*, 1981]. When the position of the balloon was compared to NOAA 7 polar day and night infrared cloud cover photographs (available from the World Data Center), thunderstorms, as identified by the measured electric field, did occur when the

balloons passed over cold clouds (-30°C) as expected. In Figure 5b the occurrence of a solar flare on February 16 (day 412), which effected flight 8 only, is indicated (by S.F.) and will be the topic of another paper.

One feature of Figures 5a and 5b is that the vertical component of the electric field from the two widely spaced balloons track each other very well. This would imply that the E_z values measured at both balloons during these times were influenced by the same large-scale current system. Since the balloon separation was up to 6000 km, it may be reasonable to assume this large-scale current system variation was representative of the global circuit. Thunderstorms account for much of the times when the two balloons' E_z values did not agree. As mentioned before, these occurrences were easily identifiable in the data set [see *Holzworth et al.*, 1986]. However, there were a few times when the E_z values did not agree (30% or greater difference) and could not be attributed directly to thunderstorms. Many of these times may be due to weakly electrified clouds or otherwise greatly different columnar resistances below the balloon [cf. *Holzworth*, 1981].

To compare the degree of similarity between the vertical component of the fair-weather electric field of two balloons, histograms of the difference (in percent) between the 10-min averaged E_z of flights 1-2 and of flights 7-8 are displayed, for 5 days, in Figures 6a and 7a, respectively. If the percentage is greater than zero, the magnitude of E_z from flight 2 (or 8) is less than that of flight 1 (or 7). The average difference, one standard deviation, and two standard deviations, are indicated. An important feature of Figures 6a and 7a is that one standard deviation of these differences is about 12 percentage points for each data set, even though the separation of balloons 7 and 8 is 3 times that of balloons 1 and 2. This implies the degree of variability in E_z was the same for both sets of balloons. We assume that the variability between simultaneous E_z measurements was due to changes in the columnar resistance in the troposphere below the balloon [cf. *Israel*, 1971; *Dolezalek*, 1972; *Markson*, 1985] and variations in the local conductivity. Another feature of Figures 5a and 5b is the high degree of variability in E_z on both the daily and short (few hours) time scales (as pointed out by *Holzworth et al.* [1984]). In other words, the planetary-scale electric field can vary significantly from hour to hour and from day to day. This is more evident when the fair-weather E_z measurements for each day were averaged together, as in Figures 8a and 8b, to produce a mean diurnal E_z (1-hour averaged). Since E_z is negative in fair weather, increases in the magnitude of E_z appear as minimums in Figure 8. The mean daily E_z magnitude for flights 1 and 2, flown in March 1983, has a single maximum about 1900 UT and a minimum at about 0600 UT (Figure 8a), which looks similar to the Carnegie data [*Whipple*, 1929] (see also, *Holzworth et al.* [1984]). However, the daily average E_z values can be considerably different from the mean. The mean diurnal variation for flights 7 and 8 (solid line in Figure 8b) has dual maxima, at about 0900 UT and 1900 UT. These dual diurnal peaks were typical for the second set of flights, which were flown in northern hemisphere winter (December 1983 to February 1984). Again, the value of the fair-weather electric field on any given day can vary significantly from

Fig 5

Figs 6 + 7

Fig 8

the mean electric field value.

5. CURRENT DENSITY

The current density is the product of the electric field and the scalar conductivity ($J = \sigma E$). Thus the current density is a derived, not directly measured quantity. Since the vector electric field was predominately vertical and the conductivity was a scalar at balloon altitudes, the vector current density was also vertical and directed downward toward the ocean. As for the case of the electric field, we approximate the vector current density with the vertical component of the current density (J_z). The total average J_z for all the balloons was $-2.4 \pm 0.4 \text{ pA m}^{-1}$ and agrees with other current density measurements [cf. *Gringel and Mühleisen, 1977; Tanaka et al., 1977*]. The value of the fair-weather current density is determined by the columnar resistance and the earth-ionosphere potential drop. Since 90% of the total columnar resistance is below 12 km [*Israel, 1973*], the variation of the upper part of the columnar resistance is small compared to the variation in the lower atmosphere [*Dolezalek, 1972*]. Also, many observers have noted that the fair-weather current density is essentially constant as a function of height [*Gringel and Mühleisen, 1977*]. Therefore the fair-weather current density should be insensitive to changes in the conductivity at balloon altitudes. The electric field measured at the balloon depends on the current density and the local conductivity [*Gringel et al., 1986*].

As with E_z , a percent difference histogram of J_z for each set of simultaneous measurements is displayed in Figures 6c and 7c, along with histograms of the conductivity (Figures 6b and 7b) and E_z (Figures 6a and 7a). From these histograms several points can be made. First, the standard deviation for J_z and conductivity are less than the standard deviation for E_z . In other words, the source for the conductivity and current density vary independently, resulting in an increased variability in the electric field. Furthermore, the standard deviations of each electrical parameter was about the same for both sets of balloons. As mentioned before, this implies that the variability of each parameter is the same, even though the balloon separation of flights 7 and 8 is 3 times that of flights 1 and 2. This similarity in the variability was consistent with the fact that all of the data in this analysis are oceanic. The oceanic data are generally perturbed the least by local effects and are the best for seeing the global variations [*Israel, 1973; Markson, 1985*]. Much of the time, the fair-weather J_z at the balloons is within 20% of each other. Both balloons measured the same large-scale current system, so the percent difference plots (Figures 6 and 7) eliminated most of the diurnal source variability (seen in Figures 8a and 8b). The variability shown in Figures 6 and 7 was probably due predominantly to the difference in columnar resistances below the respective balloons. Over land a larger standard deviation would be expected as a result of dust layers, fog and haze, and pollution [cf. *Israel, 1973; Gringel et al., 1986*], which would introduce more variation into the lower tropospheric conductivity and current density. Next, the average percent difference of the conductivity agrees with the balloon's relative magnetic latitude, as described earlier. Balloon 2 (8) is more poleward, so that the conductivity measurement is larger. A

search for the latitudinal variation of E_z and J_z , similar to that done above on the conductivity (Figure 4), did not find a significant dependence, because E_z and J_z vary significantly from day to day because of the variability of the source. Thus we cannot make any conclusions about the latitudinal behavior of E_z and J_z from this data set. However, the percent difference histograms of J_z indicate, on the average, the more poleward balloon measured a larger current density, which is consistent with other observations [Israel, 1973].

6. SIMULTANEOUS MEASUREMENTS AS A GEOELECTRIC INDEX

Recently, *Holzworth and Volland* [1986] discussed the usefulness of a geoelectric index. This index, similar in utility to the sunspot number and the magnetic K index, would be a measure of the global electric activity in the lower atmosphere. Holzworth and Volland's criteria for a useful geoelectric index could be summarized as being (1) simple to derive, (2) long in temporal length, and (3) reproducible from alternate data sets.

For in situ measurements, *Holzworth and Volland* [1986] suggested that either the electric potential Φ or the global current density J_g would be the relevant index parameter, depending on whether thunderstorms behave as voltage or current generators. Presently, there is not enough information on thunderstorm processes to determine which type of generator description is more appropriate. Many experimenters prefer using the ionospheric electric potential as an indicator of the global process [see *Markson*, 1985]. However, most methods for measuring the electric potential, employing airplanes and/or sounding balloons, are extremely labor intensive, and resulting data sets tend to be short. Thus only a nominal, low temporal resolution geoelectric index could be created. On the other hand, the superpressure balloon technique satisfies the first two points of Holzworth and Volland's criteria (simplicity and long temporal length) probably better than any other airborne method (such as sounding balloons or airplanes). Note that superpressure balloons at a slightly lower altitude have lasted for over 1 year [*Olivero et al.*, 1984]. Even at 26 km, superpressure balloons have been flown for 100 days or more (V. Lally, personal communication, 1985), so there is the potential for much larger data sets in the future. Once launched, the balloon data and location are easily monitored with satellites. With this in mind it is possible that the measurements from the superpressure balloons, such as those described here, can be used as an in situ geoelectric index. Since a sounding of electrical parameters from the ground up is needed for determining the absolute electric potential, constant-altitude balloon measurements are limited to the in situ electric field, current density, and conductivity measurements. How good are the current density data as a global process indicator? If the variability of the columnar resistance below the balloon is small and there were no local generators, then the measured current density should be proportional to Φ . In addition, if the distribution of the global resistance were also constant, then the measured fair-weather current density would be proportional to J_g . In either case, if the columnar resistance below the balloon was nearly constant and there were no

local generators, the derived current density data would be proportional to one of the relevant index parameters. In our case, all of the data analyzed were oceanic. Oceanic data are generally perturbed the least by local effects and are the best for seeing the global variations [Israel, 1973]. Also, the superpressure balloons floated well above the planetary boundary layer (PBL), so PBL-related problems at the balloon, such as turbulence and pollution, are not important. Assuming the daily variation in the columnar resistance was small, we would expect the current density derived from the fair-weather oceanic balloon measurements would be globally representative.

It is not possible, except in the case of a thunderstorm, to determine if the measurements at a single balloon were locally perturbed. However, by comparing measurements from several widely spaced balloons, it should be possible to determine which measurements were so perturbed. In other words, measurements related to the global variations should have similar values and measurements affected by local phenomena should be different. Thus we use the criteria that the difference between the simultaneous measurements must be within two standard deviations (about 20%), as described above, in order to be considered globally representative. This 20% (maximum) variation in the raw 10-min average measurements maybe due to variations in the local columnar resistance or any other weakly perturbing influence. It is unlikely that only two simultaneous measurements are sufficient for a completely reliable average, so some additional temporal averaging, of the order of a few hours, would be needed in this data set.

A geoelectric index could be easily constructed from these current density measurements. First, simultaneous data, within two standard deviations, from each day are averaged together to produce a mean diurnal global current density (J_{MDG}) curve. This J_{MDG} would be equivalent to a 1-day Carnegie curve and represents the mean daily variation of the global circuit. Specifically, the J_{MDG} curve can be stated as

$$J_{MDG}(t) = \frac{\sum_{\text{days}} J_R(t)}{\text{total days}} \quad (3)$$

where $J_R(t) = \langle J_i(t) \rangle_{\text{balloons}}$ for which only data with $|J_i^1 - J_i^2| < 0.2 * \langle J_i(t) \rangle$ are used, that is, only data within two standard deviations.

Since evidence suggest that the shape of the average global circuit curve varies seasonally [Whipple, 1929; Ogawa, 1969], a new J_{MDG} curve should be created at least seasonally for long-term data sets. The geoelectric index is then made by subtracting J_{MDG} from J_R for each day and then normalizing (dividing by the average current density for the entire data set). Mathematically, this can be symbolized as

$$\text{geoelectric index} = \frac{J_R(t) - J_{MDG}(t)}{\langle J_i \rangle} \quad (4)$$

where $J_R(t)$ is the representative current density as defined above and $\langle J_i \rangle$ is the average current density ($\langle J_i \rangle = \frac{1}{N} \sum_{i=1}^N \int J_i(t) dt$, where N is the number of balloons for the

interval 7). We used a value of -2.4 pA m^{-1} for the average current density. The subtraction of J_{MDG} removes the average "expected" daily variation from the index. The index is then averaged for a 3-hour time resolution (similar to K_p magnetic index). Times when the index is higher than the mean may be caused by an increase in the global source current, an increase in the global columnar resistance (assuming the source current remains unaffected), or both. Likewise, a decrease in the global source current and/or global resistance from the mean would cause the index to become negative. Figures 9a and 9b show the 3-hour averaged geoelectric indexes with uncertainties for the two sets of data. A value of 1.0 (-1.0) would mean the global current density is 100% higher (lower) in magnitude than the expected average value at that time. The gaps in the index are due to times when either there were no data or when the two balloons measured current densities different by more than $0.2 * < J_z >$. The uncertainty was determined by the number of data points per 3-hour averaging slot (always three or more) and the amount of relative scatter. The average uncertainty is about ± 0.1 . The index for flights 1 and 2 (Figure 9a) shows a decrease in the first day or so, then fluctuates about the mean for about a week, and then increases suddenly. The sudden decrease near hour 320 appears to be real. The index of flights 7 and 8 (Figure 9b) shows higher than mean values for the first 3 days and low values for the last 3 days. Besides a general daily trend, these indexes show there can be significant source variability of the order of a few hours. This supports the preliminary findings on the first set of data by *Holzworth et al.* [1984]. Although the data were purely from the southern hemisphere, the evidence suggests the data may be globally representative, since the separation of the balloons was clearly of a global scale (6000 km separation for balloons 7 and 8). This is not unreasonable if the ionosphere is approximately an equipotential surface.

A disadvantage of this index is that it can only provide information on the relative changes in strength of the sources. This index indicates when sources were more "active." However, it can not give information on location and strength of any individual source.

Finally, this geoelectric index appears to show the variability of the global circuit. Are the variations seen in our geoelectric indexes reproducible in other data sets? Presently, this is the outstanding question. At this time we have not sufficiently determined if this index is indeed a good representative of the global electrical environment because of the lack of comparative data sets. We offer our indexes for just that purpose.

7. CONCLUSIONS

In this paper we have examined the conductivity, vertical component of the electric field, and vertical component of the current density. Special emphasis was placed on the constant-altitude, simultaneous measurements from widely spaced balloons. The results of our analysis show that the conductivity was nicely described by a simple ionization-rate parameterization depending on the geomagnetic latitude. The variability of all the electrical parameters, as parameterized by the standard deviation of the

Fig 9

difference between two simultaneous measurements, were independent of the balloons' separation. Perhaps one of the most important results was that the current densities derived from simultaneous balloon measurements were within 20% much of the time, even though the balloons were up to 6000 km apart. This implies that the measurements at both balloons were probably globally representative and not influenced by local generators. Thus simultaneous balloon measurements of this type could be used to determine characteristics of the global circuit. These current density measurements already indicate the global current source is significantly variable on a daily and few-hour time scales. Finally, we examined the advantages and limitations of using the simultaneous current density values as a possible geoelectric index, as proposed by *Holzworth and Volland* [1986]. Even though this index can not make any determination on the location and strength of any one source, these simultaneous measurements provide a simple, easy to produce, long-term estimate of the global electric environment. However, the reproducibility of such an index in other data sets remains unproven at this time.

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Fig. 1. Trajectories of the two sets of EMA balloons about the southern hemisphere.

Fig. 2. Flight times of the two sets of EMA balloons. Arrows indicate when the loss of superpressure was first noted. White gaps indicate times when no data were available from the satellite data collection facility.

Fig. 3. (a) Positive and negative polar conductivity of flight 1 for 5 days.
(b) Positive and negative polar conductivity of flight 7 for 5 days.

Fig. 4. Magnetic latitude verse conductivity for payloads 1, 2, 5, 7, and 8. The lines represent a least squares fit to $(A + B \sin^4 \lambda)^{1/2}$.

Fig. 5a. Simultaneous constant-altitude vertical electric fields of flights 1 and 2 for 5 days.

Fig. 5b. Simultaneous constant-altitude vertical electric fields of flights 7 and 8 for 5 days. S.F. designates the occurrence of a solar flare on day 412, which effected flight 8 only.

Fig. 6. Histograms of the difference (in percent) for the simultaneous measurements of the vertical component of the electric field, conductivity, and derived vertical component of the current density from flights 1-2. Lines show the average difference and one and two standard deviations marks, with Σ as the symbol for the standard deviation.

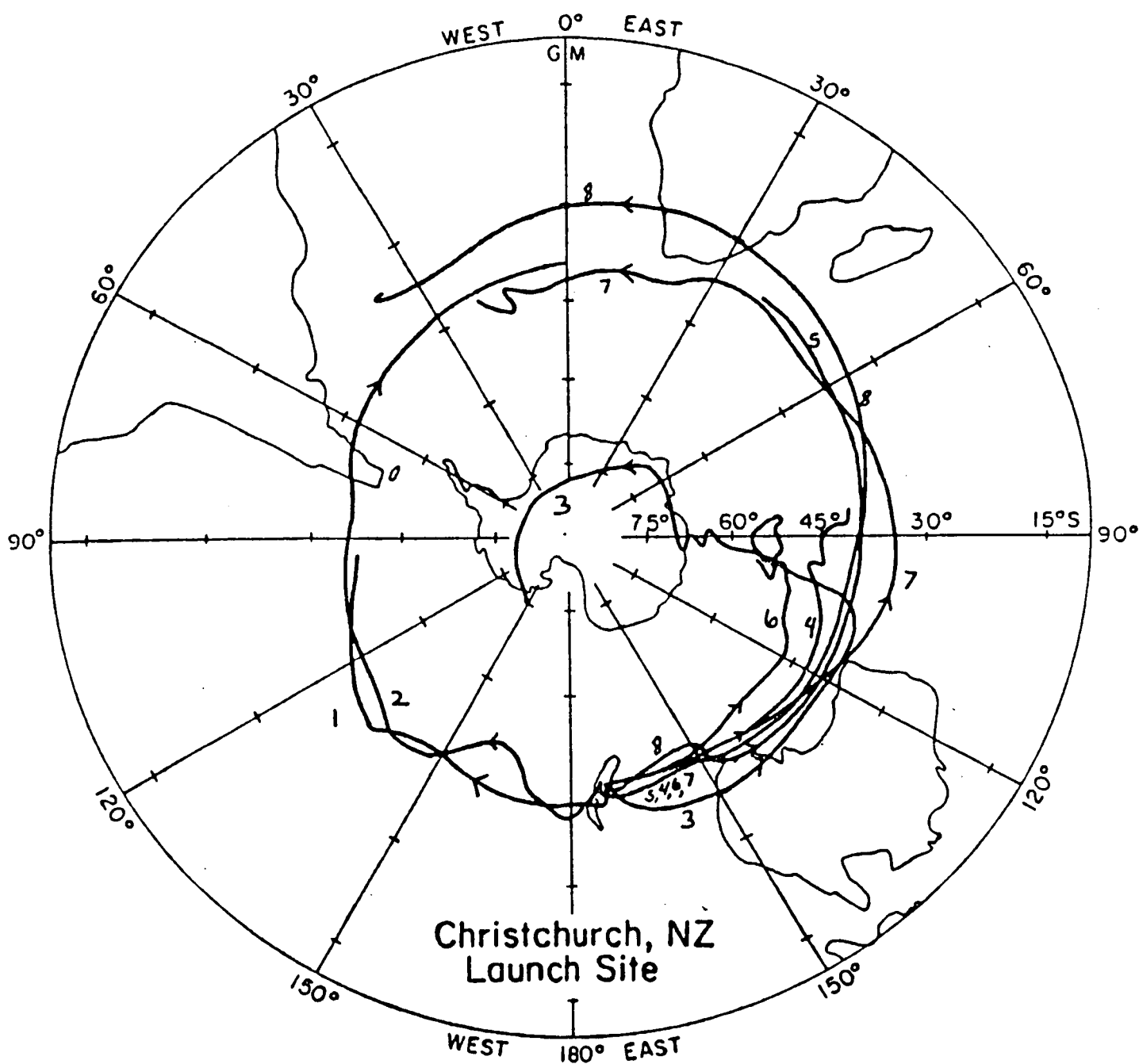
Fig. 7. Same as Figure 6 for flights 7 and 8.

Fig. 8a. The simultaneous fair-weather E_z of flights 1 and 2, with the 3-hour averaged E_z (solid line).

Fig. 8b. The simultaneous fair-weather E_z of flights 7 and 8, with the 3-hour averaged E_z (solid line).

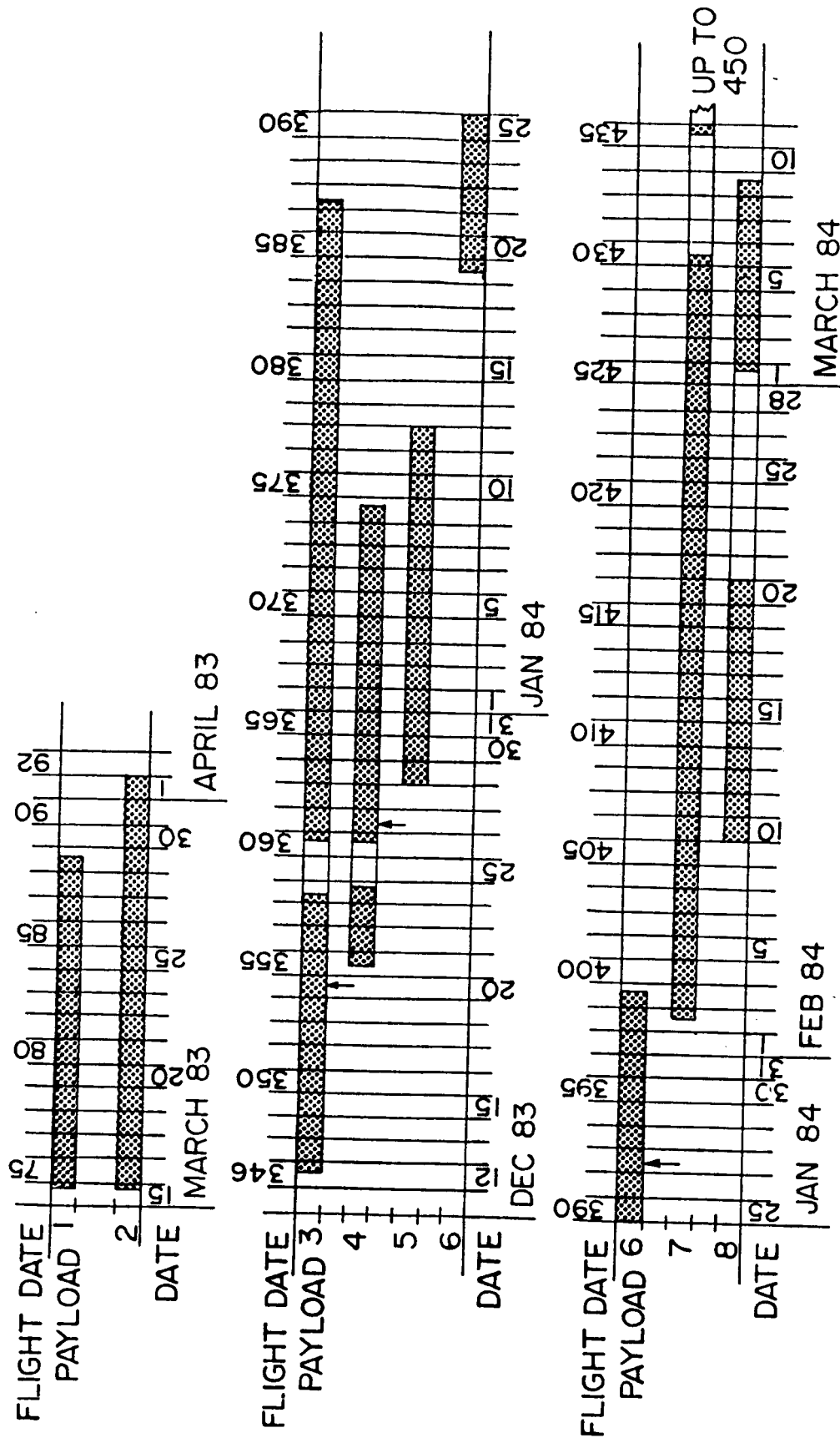
Fig. 9a. The geo-electric index, with uncertainty derived from the simultaneous J_z measurements of flights 1 and 2.

Fig. 9b. The geo-electric index, with uncertainty derived from the simultaneous J_z measurements of flights 7 and 8.



**SUPERPRESSURE BALLOON TRAJECTORIES
1983/1984**

Figure 1



EMA FLIGHT DATA COVERAGE 1983/84

Figure 2

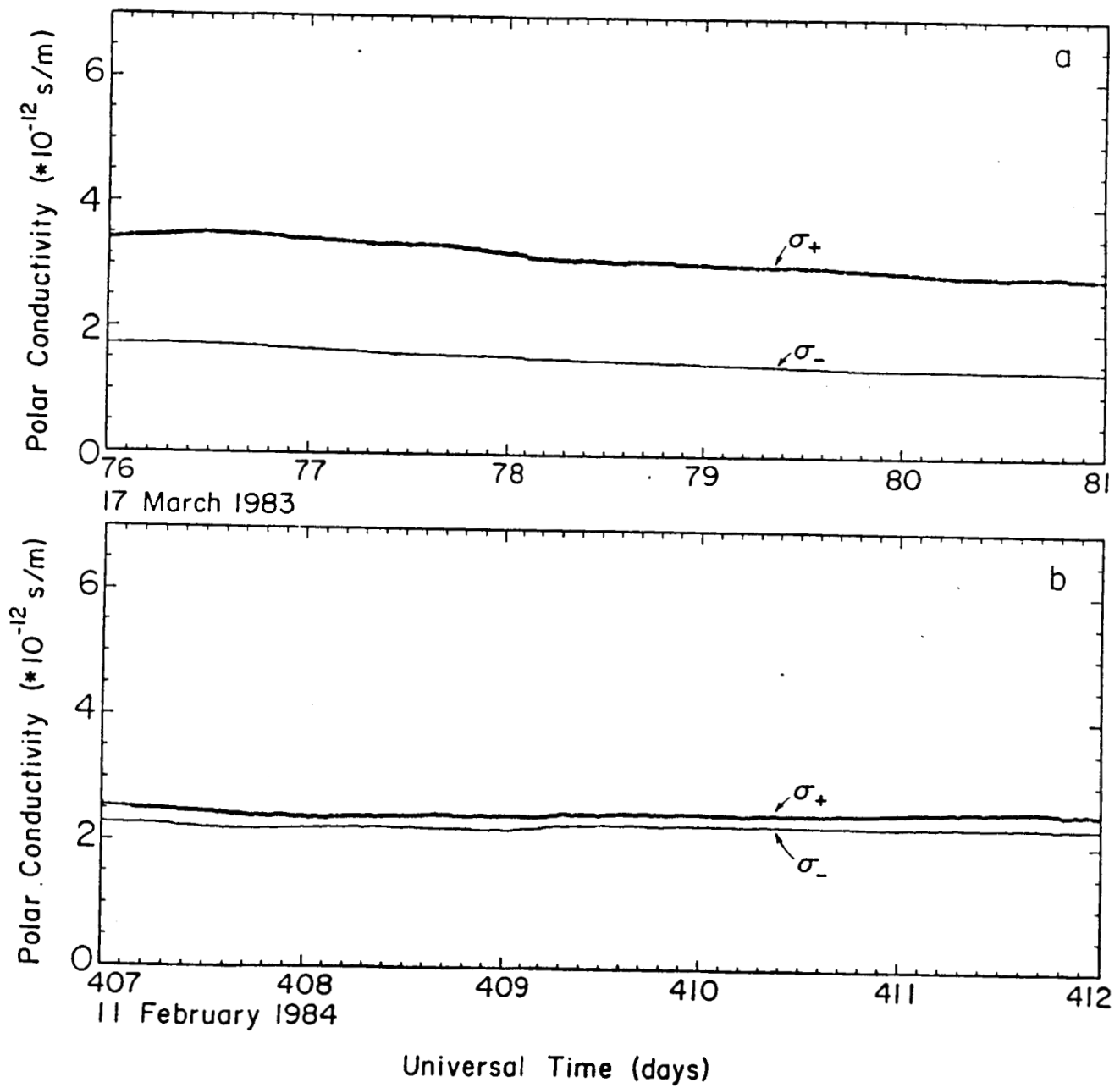


Figure 3

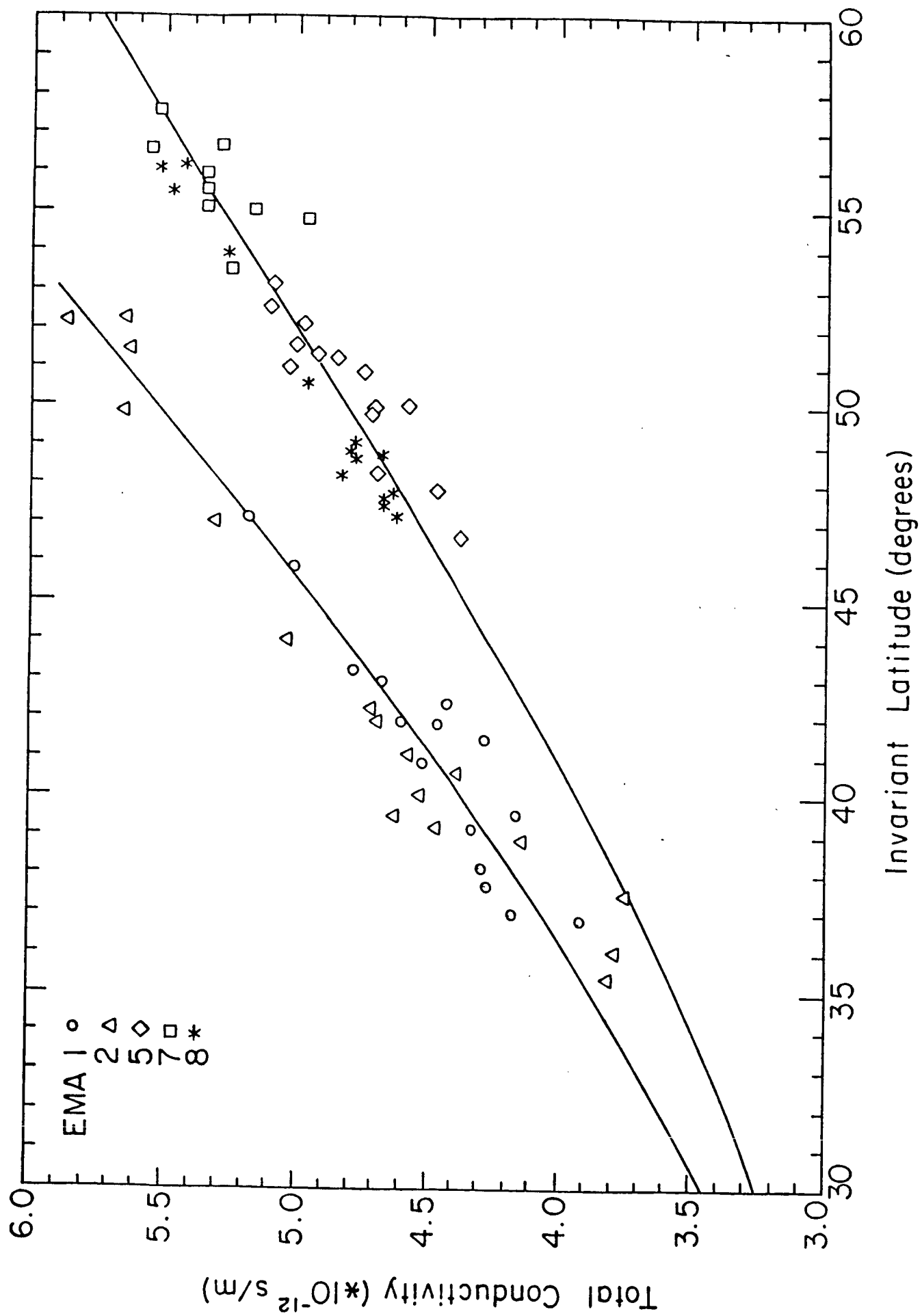
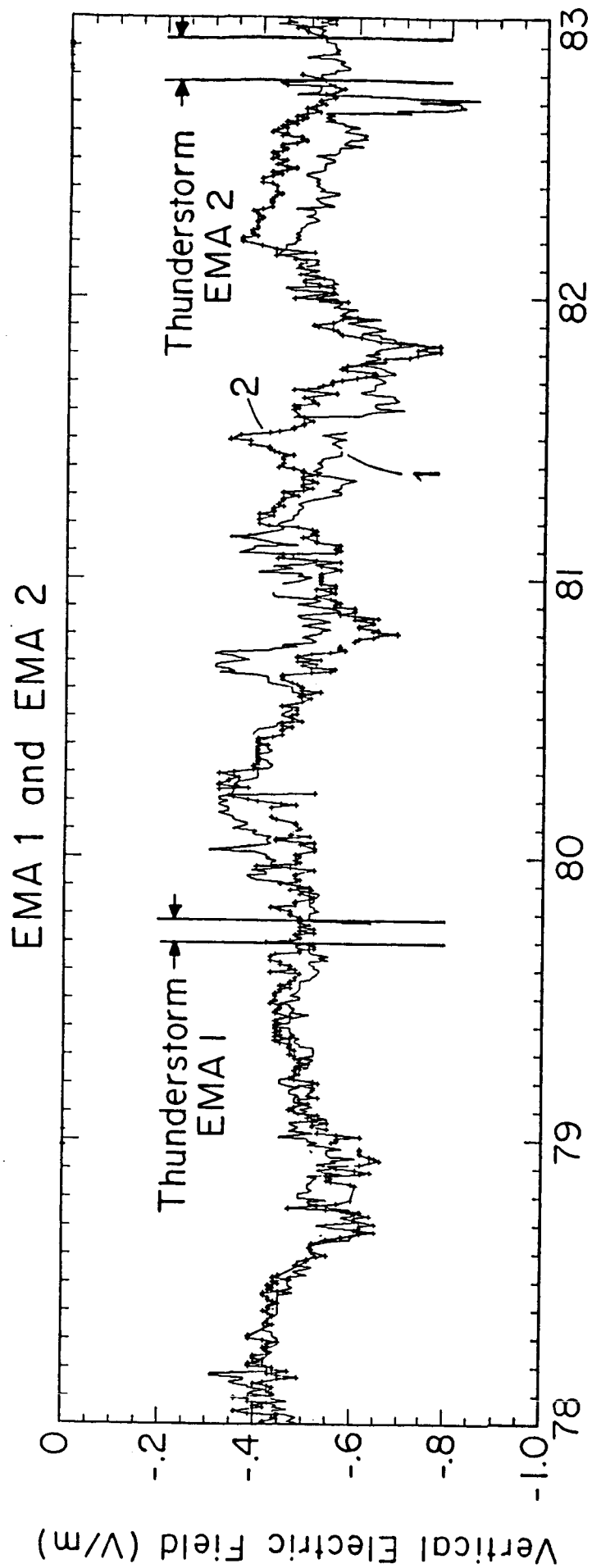
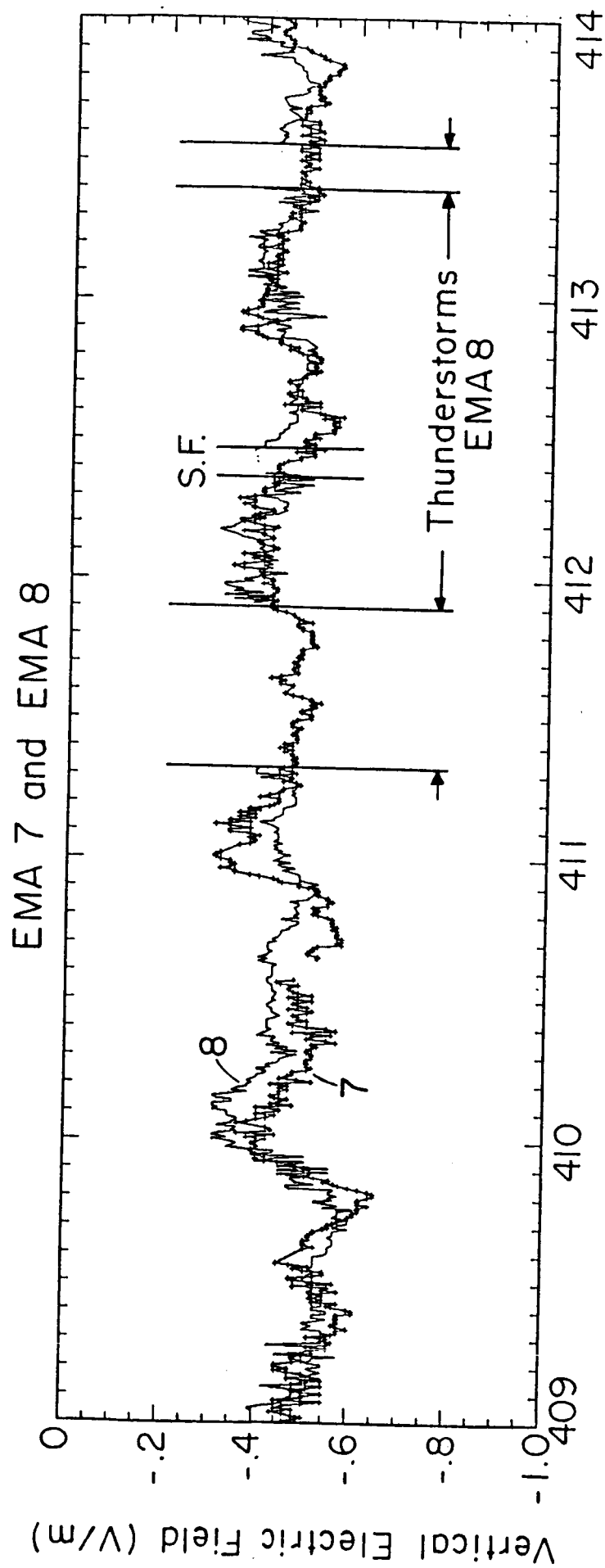


Figure 4



Universal Time (days) (19 Mar. - 23 Mar. 1984)

Figure 5a



Universal Time (days) (13 Feb. - 17 Feb. 1984)

Figure 5b

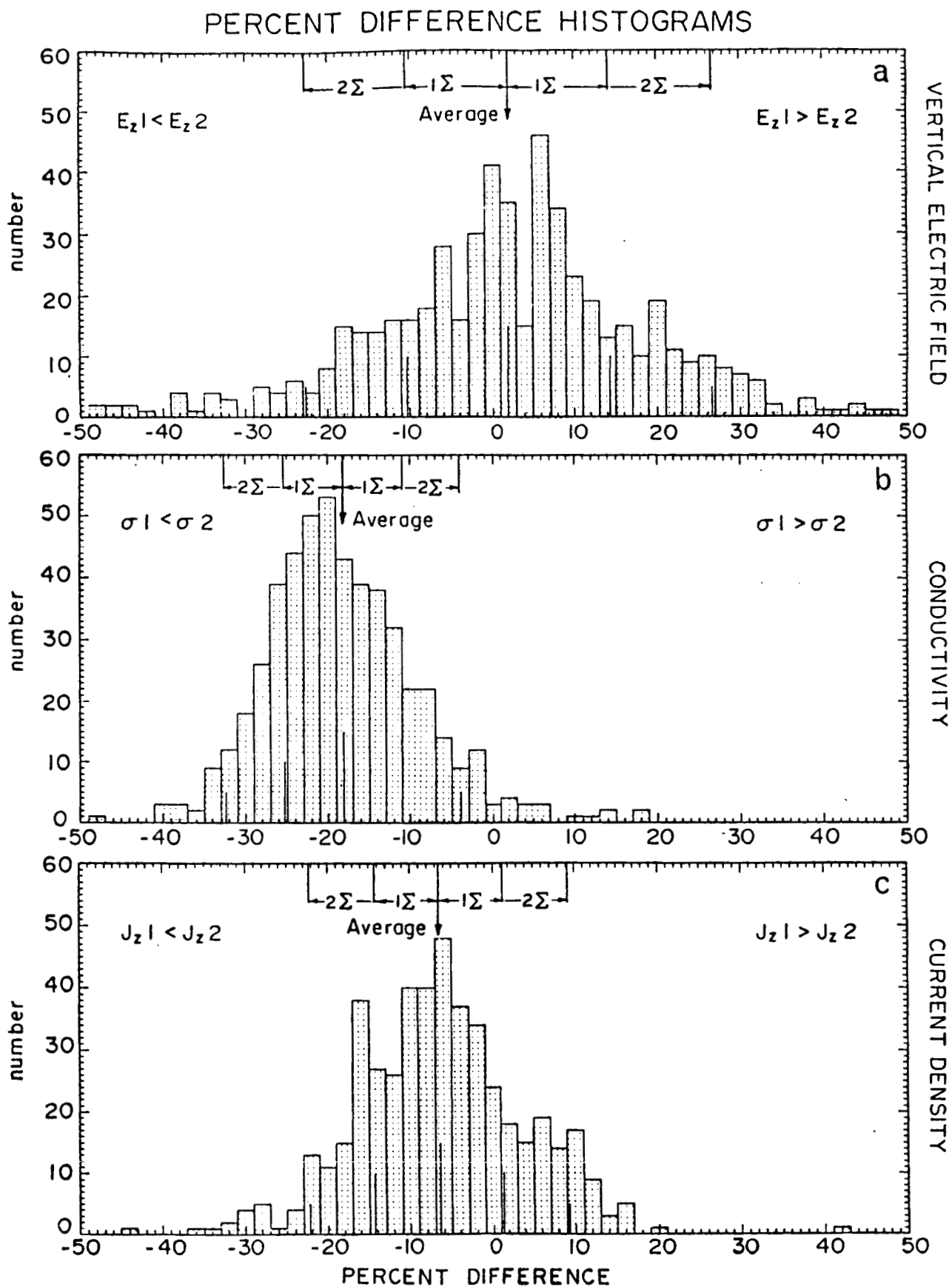


Figure 6

PERCENT DIFFERENCE HISTOGRAMS

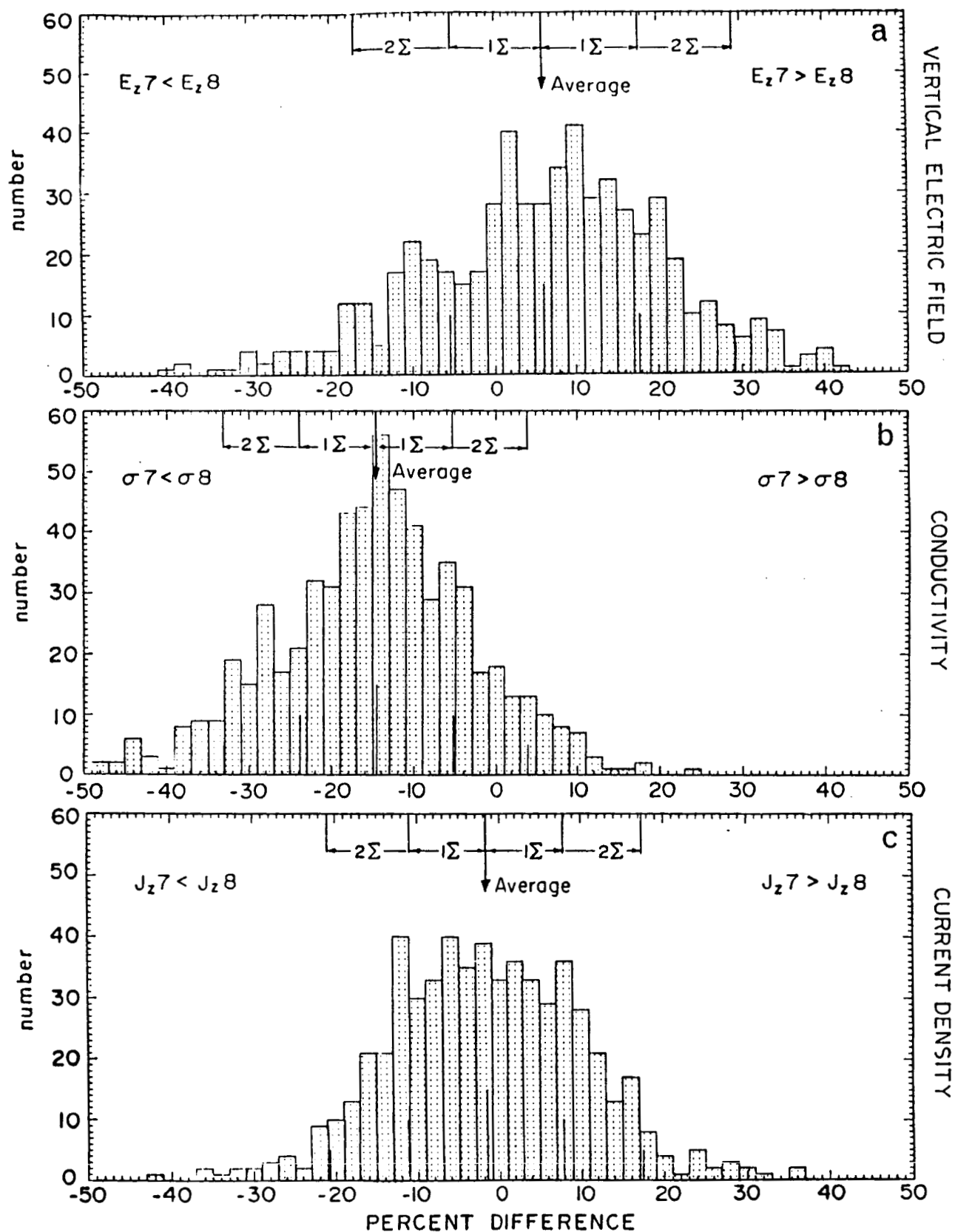
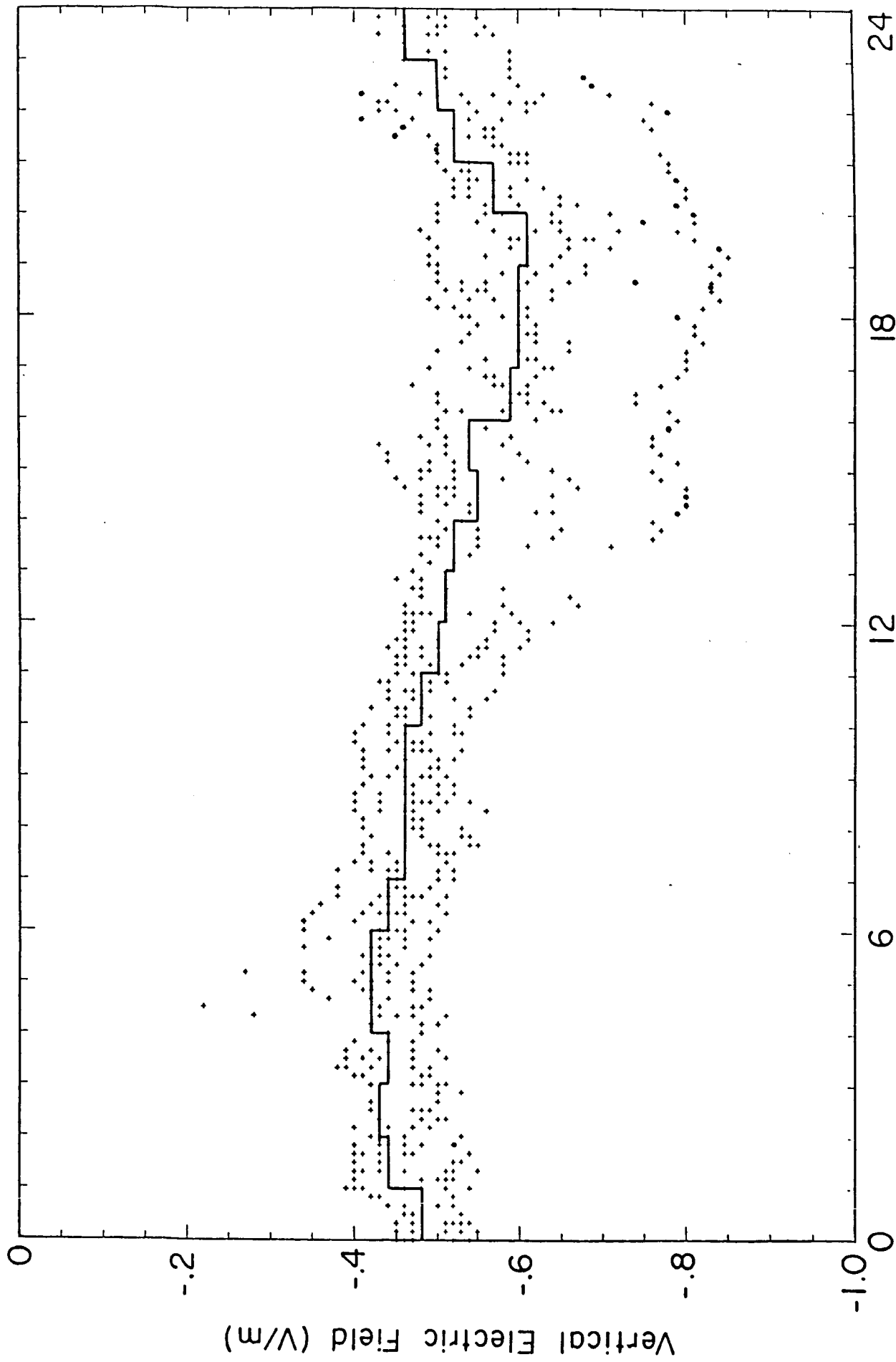


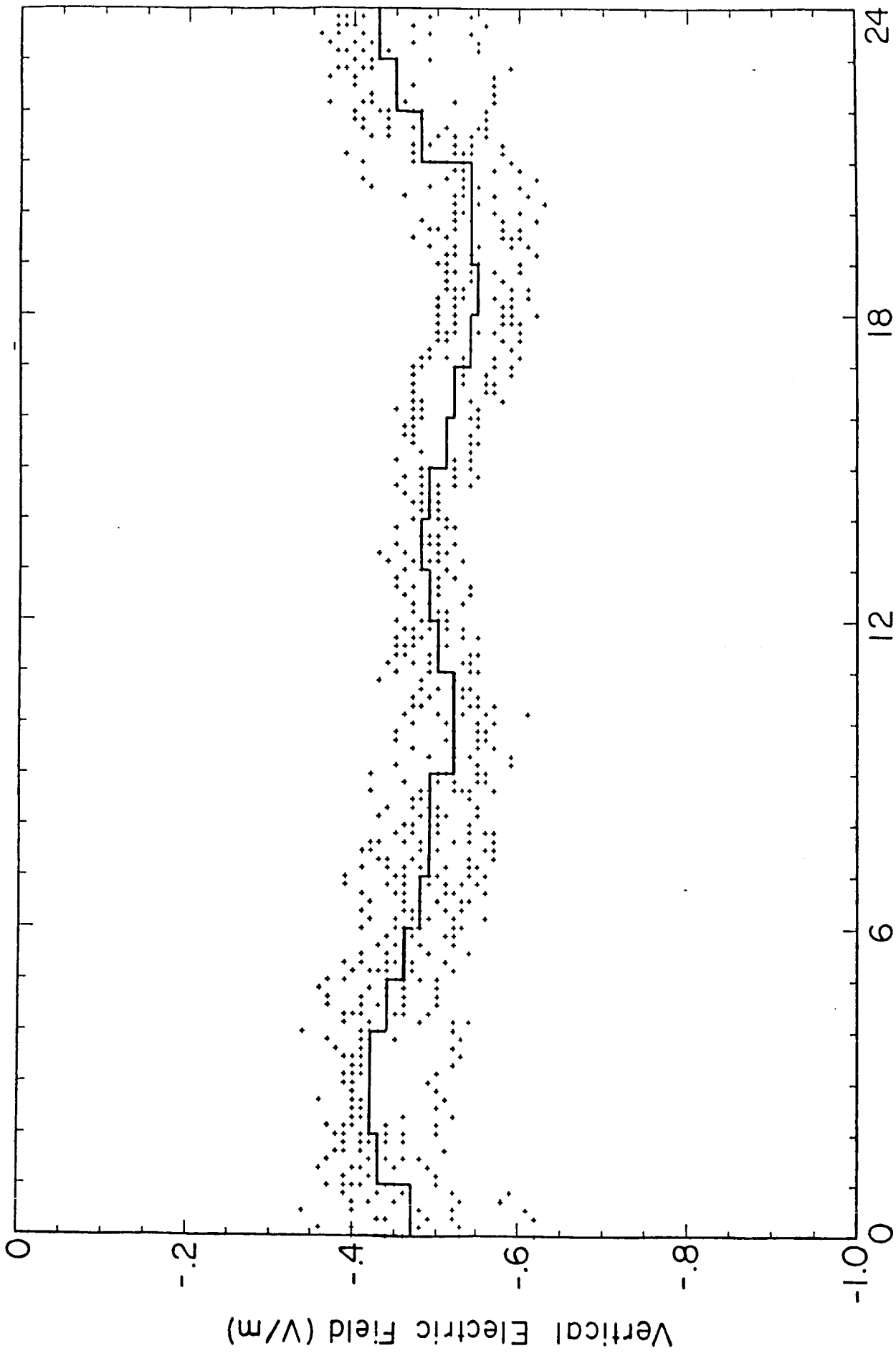
Figure 7

EMA 1 and EMA 2



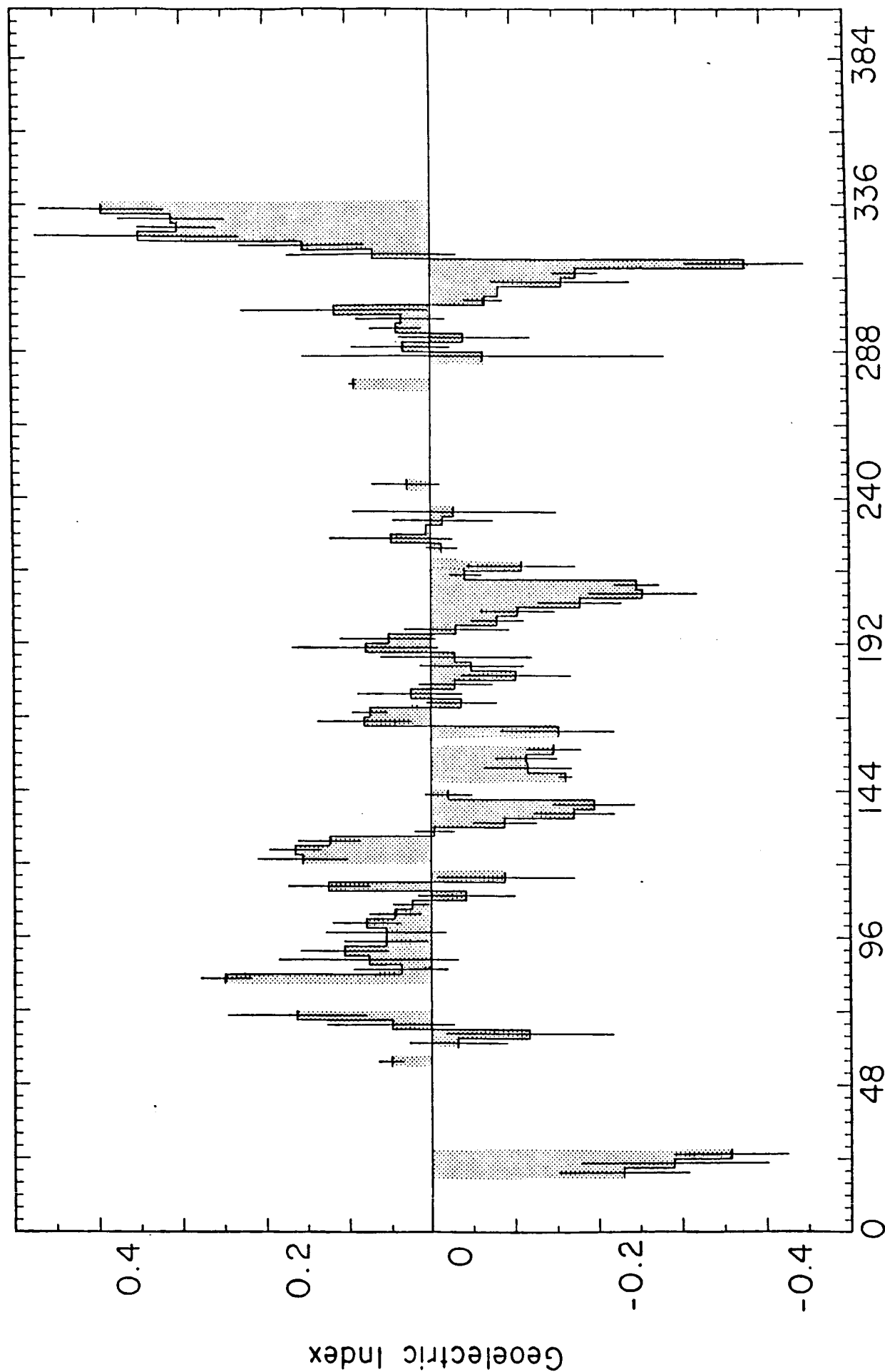
Universal Time (hours) for Days 78 to 88 (19 Mar. - 29 Mar. 1983)

EMA 7 and EMA 8



Universal Time (hours) for Days 406 to 413 (10 Feb. - 17 Feb. 1984)

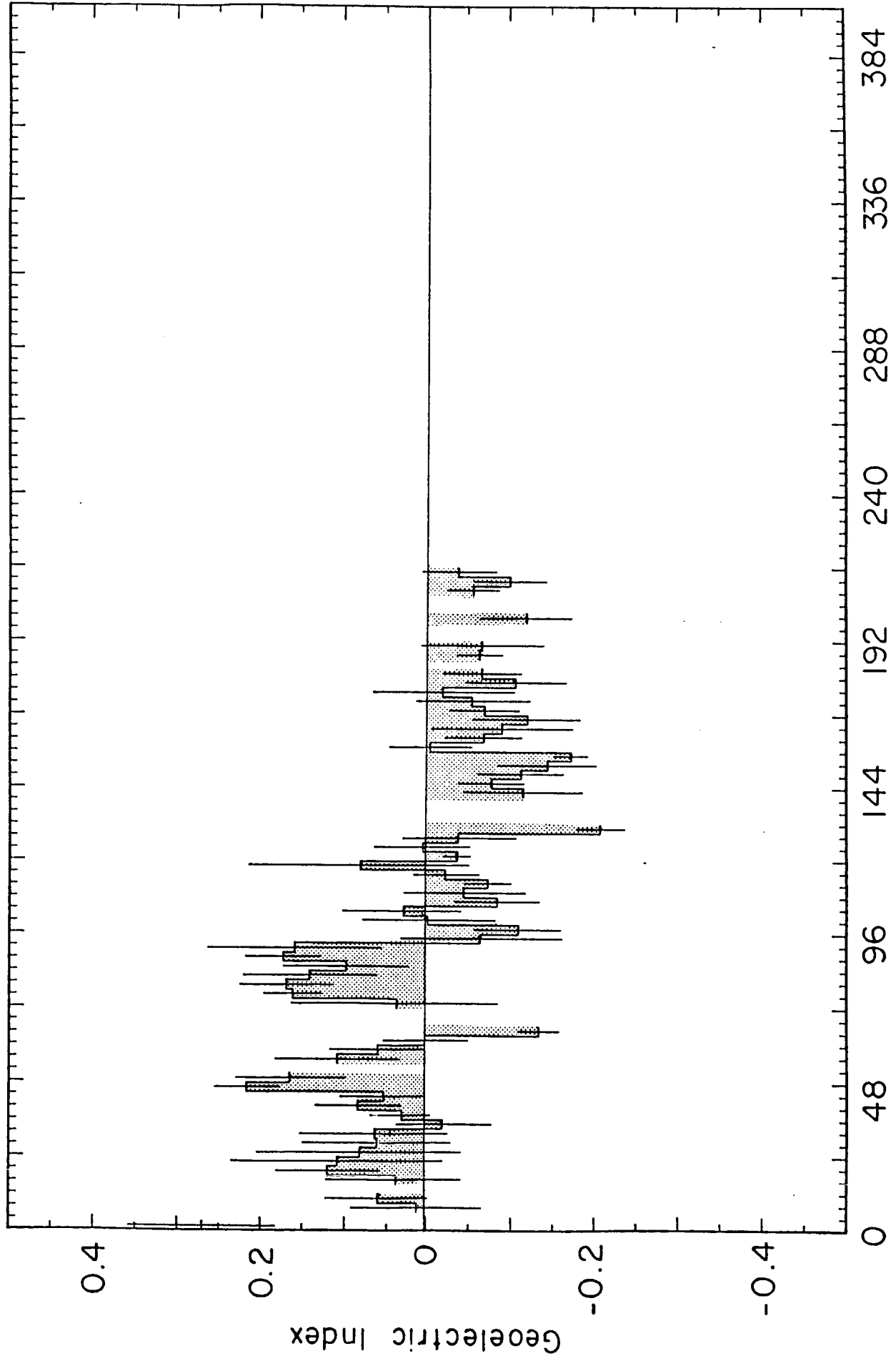
EMA 1 and 2



Universal Time (hours) for Days 74 to 88 (15 - 29 March 1983)

Figure 9a

EMA 7 and 8



Universal Time (hours) for Days 406 to 420 (10 - 24 Feb. 1984)